CANOPY COLLAPSE

OF DRIED PEA CROPS

by

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DECLARATION

This thesis and the work presented herein is my own work except where otherwise indicated.

M.R. Holland, August 1988.

DEDICATION

This thesis is respectfully dedicated to all those who, through thought, word, or deed, demonstrate their belief in the dignity of our planet and all her people.

"When will there be a harvest for the world ?"

The Isley Brothers.

ABSTRACT

Interest in the dried pea crop in Europe has revived in the last few years, and it is now the sixth largest (by area sown) in the U.K.. A major problem is that almost all varieties lodge badly several weeks before harvest, with minimum losses estimated at about £6 million. So-called 'leafless' varieties have been bred which have much improved standing ability, though unfortunately yields are lower than for conventionally leaved plants

This is the first study to investigate the forces acting on pea canopies due to the wind, rain, and weight of the canopy. A number of varieties were used, including conventional, semileafless, leafless, and (comparatively) stiff stemmed phenotypes. Measurements of canopy structure (including mechanical attributes of stems and petioles and distribution of fresh mass etc. with height) were taken at, or around, the time of lodging. Wind profiles were measured throughout the 1984 season over crops with the different leaf morphologies. This part of the study was continued with measurements of drag exerted on isolated leaves and pods in a wind-tunnel. A model of standing ability has been developed from the results, which shows that collapse of pea canopies occurs mainly through the weight of the canopy being too great for the stems and petioles to support as they dry out and weaken in late season. Unlike other crops, wind is only of

secondary importance, momentum so absorbed being widely dissipated through the manifold connections between plants. Estimates of the increase in the flexural rigidity of stems necessary to give improved standing ability have been made.

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CONTENTS

List of symbols

A Area (m^2).

a,b Empirical coefficients from Landsberg and James' within canopy profile equation.

C_d Drag coefficient of an individual canopy element.

$\bar{C_d}$ Drag coefficient of an individual canopy element held at the mean within canopy angle between airflow and leaf axis.

C_D Bulk canopy drag coefficient.

$\bar{C_M}$ Effective canopy drag coefficient of an average canopy element.

c_p Specific heat of air at constant pressure ($J\ kg^{-1}\ K^{-1}$).

D Deflection of a beam under stress (m).

d Zero plane displacement (m).

F Force due to wind-drag (N).

F_H Total force acting horizontally on unit ground area of crop ($N\ m^{-2}$).

F_V Total force acting vertically on unit ground area of crop ($N\ m^{-2}$).

F_{Rv} Compressive force resulting from the vertical component of the impact of rain onto a crop, per unit ground area ($N\ m^{-2}$).

F_{wc} Compressive force on a canopy due to the weight of the crop per unit ground area ($N\ m^{-2}$).

F_{wR} Compressive force on a canopy due to the weight of water carried on the surface of leaves etc after rainfall, per unit ground area ($N\ m^{-2}$).

f Drag force acting on canopy predicted from drag coefficient measurements (N m^{-2}).

g Acceleration due to gravity (9.81 m s^{-2}).

H Flux density of sensible heat in air (W m^{-2}).

h Canopy height (m).

I Moment of inertia (kg m^2).

I_g geometrical moment of inertia, or second moment of area (mm^4).

k von Kármán's constant (0.41).

L Monin-Obukhov stability length (m)

l length (m).

l_E Effective length of sample in Euler's formula for buckling (m).

l_{min} minimum length of sample that will buckle under a load (P) (m)

M Moment acting on a beam (N m).

M_2 Contribution to the total moment acting on a stem, arising from displacement of the canopy (N m).

M_{max} Moment necessary to break a stem (N m).

m Canopy mass (kg).

m_R Total mass of rain drops incident per unit ground area per second (kg m^{-2} s^{-1}).

P Load (N).

P_E Euler load (that necessary to cause the buckling of a given sample) (N).

p_d Shelter factor.

R Radius of stem (m).

r Radius of central cavity within a stem (m).

R_{min} Minimum radius of stem necessary to resist a given force (N) without breaking (m).

RGR Relative growth rate (g g^{-1} day^{-1}).

Ri Richardson number.

S_d Cumulative area of vegetation per unit horizontal area (m^2 m^{-2}).

T Temperature (K).

T_a Temperature at reference level z_a (K).

t Time (s).

u Wind-speed (m s^{-1}).

'u Hypothetical uniform within canopy wind-speed that gives the same drag as the canopy wind profile (m s^{-1}).

u_* Eddy (friction) velocity (m s^{-1}).

v_t Terminal velocity (m s^{-1}).

W Dry mass of plant material (kg).

x Fetch (m).

'x Parameter in Miranda's stability correction equation.

Y Young's modulus (N m^{-2}).

$Y.I_g$ Flexural rigidity (N m^2).

z Height above ground (m).

z_a Reference level for calculation of Ri (m).

z_0 Roughness length (m).

Greek letters

α Extinction coefficient in Thom's within canopy wind profile equation.

β Extinction coefficient in Cionco's and Inoue's

within canopy wind profile equation.

θ Potential temperature (K).

ρ Density of air (kg m^{-3}).

σ Stress (N m^{-2}).

τ Shearing stress (N m^{-2}).

ψ Stability correction parameter.

CHAPTER 1

INTRODUCTION

Since the early 1970s the European Community has been aware of the need for a home grown vegetable protein crop to reduce dependence on expensive imported soya (Schiratti, 1983). As soybeans are not well suited to conditions across most of Europe dried peas, beans and lupins have been studied as possible alternatives. The dried pea (*Pisum sativum*) is favoured for a number of reasons:

i) Protein yield per hectare is similar to that of soya, and the protein is of good quality for animal and human consumption (Snoad, 1980).

ii) No toxic or bitter factors are present.

iii) Varieties suited to growth over most of Europe are already available.

iv) Improvement of yield from current averages of about 3 t/ha to 5 t/ha seems possible. Between 1970 and 1980 yields in the eastern counties of England increased from 1.87 to 3.22 t/ha on average (Murphy, 1980). In trials run by the Processors and Growers Research Organisation two varieties yielded 4.2 t/ha (PGRO, 1984 b). Heath and Hebblethwaite (1985 a) found yields up to 5.7 t/ha, whilst in the Netherlands yields of 7 t/ha have been reported.

A major objective for pea breeding programmes is to improve the poor standing ability of the crop, which reduces yield and hence makes the crop unattractive to farmers. As the plants dry out in the period leading up to harvest, the canopy becomes unstable and lodging usually occurs. The crop is then more difficult to harvest and tends to retain moisture, creating favourable conditions for the spread of disease, staining of seed, and even premature germination. Some published figures for associated losses are given in table 1.1. In the very wet summer of 1985 many growers in Britain found it impossible to harvest their dried pea crops and instead ploughed them back into the ground. Whilst similar losses have been reported for other crops (Aganovic and Miletic, 1972, for example, reported losses for barley of up to 68% when lodging occurred early in the season), pea crops differ in that most varieties lodge without fail as the canopy dries.

The importance of lodging in general is evident from the fact that 7% of insurance payouts to farmers in the U.S. result from wind damage (Boyer, 1982). Earlier studies have concentrated on forests and cereals. Despite the upsurge of interest in the dried pea crop since the mid-1970s, this is the first study to address the problem of the collapse of pea canopies from a physical perspective.

Table 1.1 Reported % losses through canopy collapse in dried pea crops.

Author	% loss	Source of loss	Comments
Proctor (1963)	13 - 47%	Total	Hand harvested
Anon. (1970)	50 - 80%	Total	
Davies (1977)	up to 80%	Total	
Murphy (1983)	5 - 40%	Staining	From Ireland
Snoad (1980)	8 - 10% (min)	Staining	Conventional varieties
	2% (average)	Staining	A leafless variety
Kielpinski (1982)	2.5%	Staining	A leafless variety
	11.2%	Staining	Conventional plants

To analyse the standing ability of a plant or crop it is necessary to use techniques developed primarily for the engineer. A first step in the structural analysis of a crop will be to measure Young's modulus (Y), the second moment of area (I_s), and the critical bending moment (M_{max}) (the moment which just causes failure in the element under examination) of the structural elements of the canopy (stems and petioles). Given that these quantities are rarely, if ever, encountered in most fields of biology, it is worthwhile pausing to consider what, precisely, they refer to, and what significance they each have for studies related to lodging.

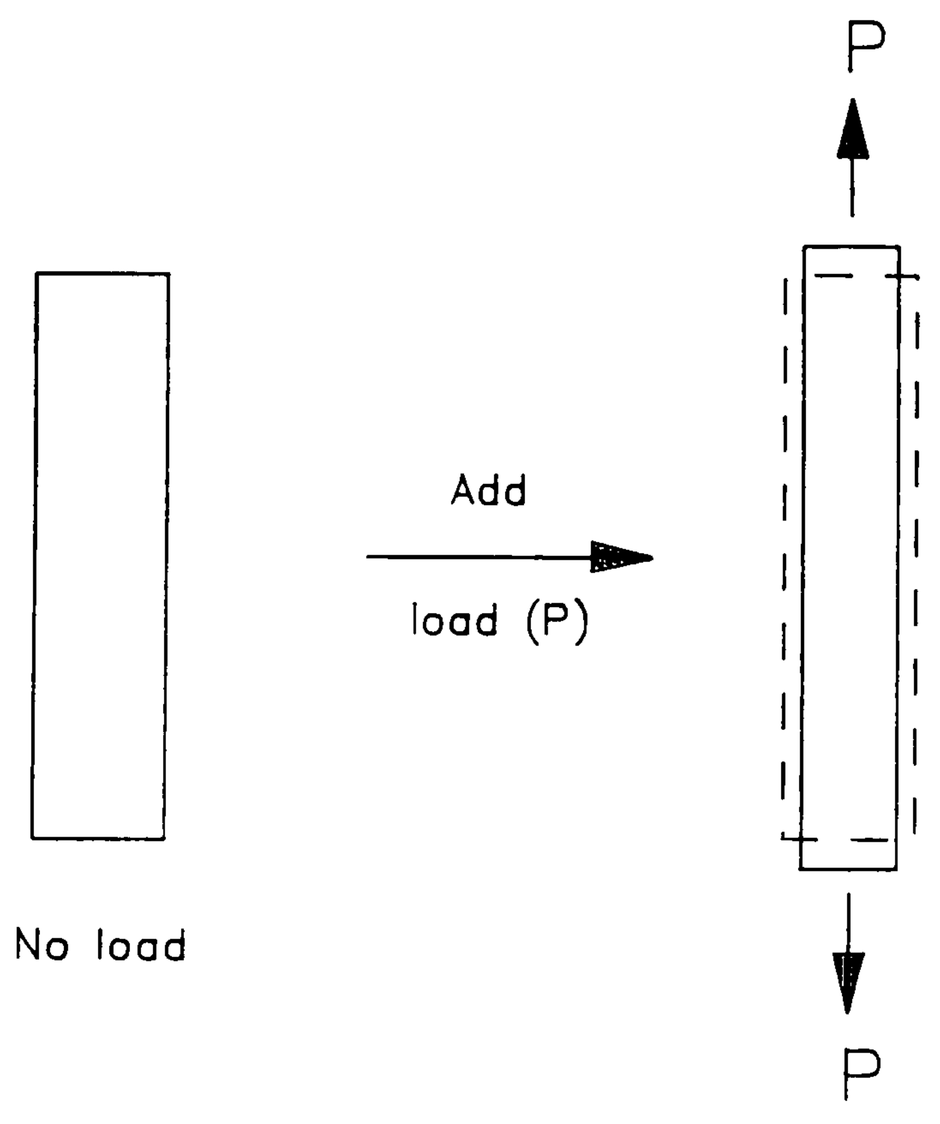
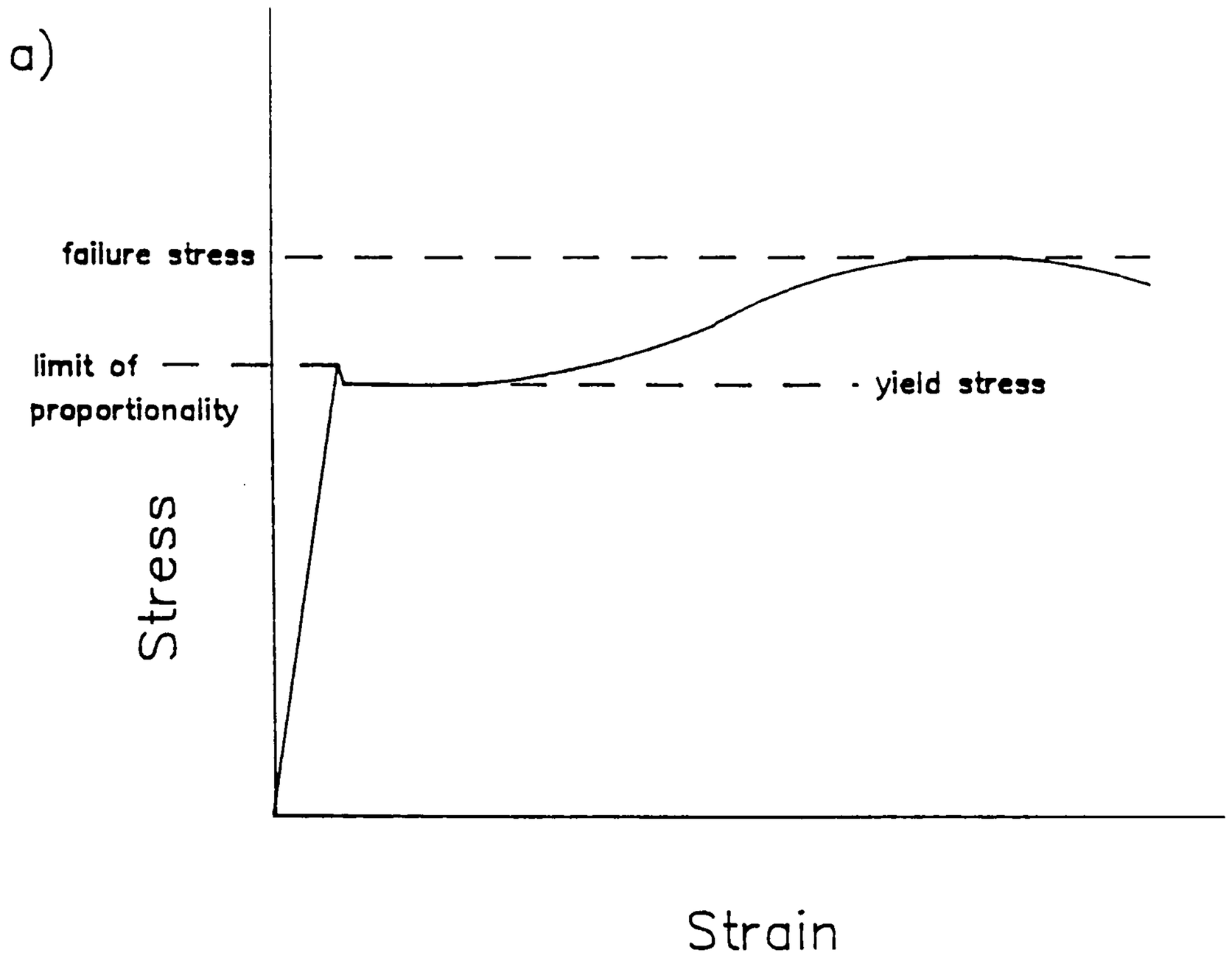


Figure 1.1 Extension of a sample under the influence of a tensile load, (P).

Let us consider a sample of an elastic material, held under a tensile load (P), as in figure 1.1 (an elastic material is defined as one in which the strain (change in dimension/ original dimension) disappears when the stress (force/area) causing that strain is removed).

Examples of relationships between applied load and deformation of samples of elastic materials taken from Graves-Smith (1974) are given in figures 1.2(a) and 1.2(b). As the load is increased, elongation of the sample is proportional to the load, up to the point known as the limit of proportionality. (Y) is calculated as the ratio of stress to strain for the region leading up to the limit of proportionality. In general the limits of proportionality and elasticity are the same, though this is not always the case (see McDonagh *et al*, 1977). Beyond the elastic limit, deformation becomes permanent, and accordingly the sample will not return to its original dimensions on removal of the load. Subsequent increase of the load may take the sample to a yield stress where strain increases greatly for little or no increase in load (figure 1.2a). Alternatively there may be no distinct yield stress, (figure 1.2b). In both cases the sample eventually fails as the load increases. Given that (Y) is only calculated for a part of the stress/strain curve, it is clear that it cannot be applied when strain exceeds the limit of proportionality.



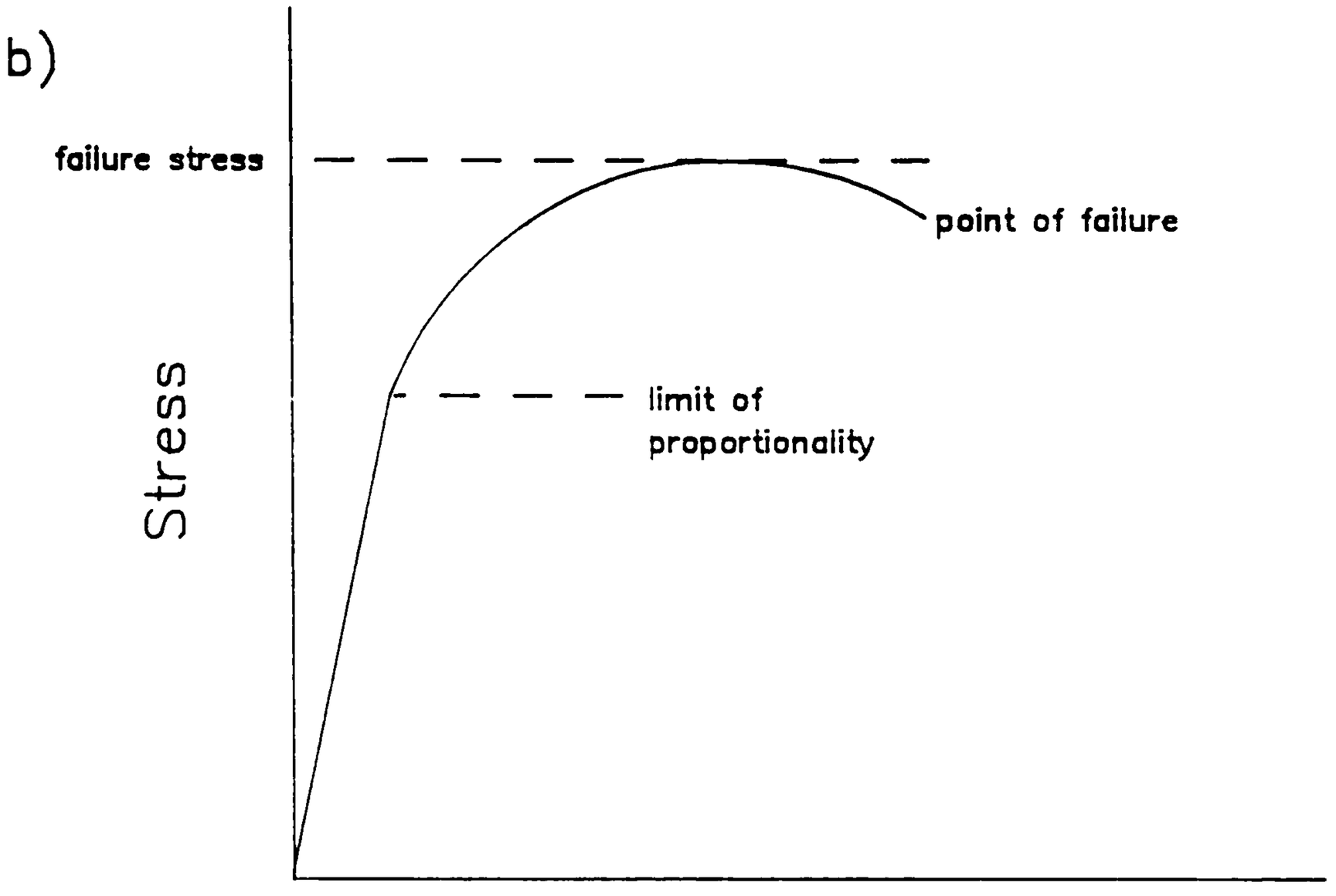


Figure 1.2 Relationships between stress and strain for samples of elastic materials under tension. (Y) may be calculated as the ratio of stress to strain in the region below the limit of proportionality. In (a) the sample shows a distinct yield stress just beyond the limit of proportionality, where the strain becomes much greater for little or no increase in stress. In (b) there is no distinct yield stress, though beyond the limit of proportionality strain increases ever more rapidly with increased stress until the sample fails.

(I_g) is a measure of the manner in which the area of a cross section is distributed about an axis. It is calculated by subdividing (in imagination) the cross section of a sample into a large number of elements, multiplying the area of each by the square of its distance from the axis and summing the products from all elements of the cross section. Units are, therefore, metre^4. Fortunately, simple formulae for the calculation of (I_g) for homogeneous beams and tubular structures (those forms of most interest to lodging studies) are available (see, for example, Morley, 1953).

It is worth emphasising that (I_g) is also referred to as the moment of inertia in some texts (eg. Den Hartog, 1949; Jones, 1983). The use of this term may cause confusion with the moment of inertia (I) (Wainwright *et al*, 1976), which is used in studies of the rotation of bodies around an axis. (I) is calculated (in theory) by subdividing the body under examination into a large number of particles, multiplying the mass of each particle (rather than the area of each element of the cross section) by the square of its distance from the axis of rotation, and summing these products for all particles present, with units of kilogram.metre^2. The two are clearly not equivalent and must on no account be confused.

(Y) and (I_g) are often given in the combined form of the flexural rigidity ($Y.I_g$) as they both contribute to stiffness; for a given stress, the strain induced in a sample will be lower the higher the value of ($Y.I_g$). To illustrate the practical significance of ($Y.I_g$) it is useful at this point to study the theory of the bending of beams, which has been used in the analysis of lodging in trees and cereals. Stephens (1970) gives the following assumptions associated with this theory;

i) The beam is originally straight and the radius of curvature is large in comparison to the cross section.

ii) The material is homogeneous, elastic, and obeys Hooke's law.

iii) (Y) is the same in both tension and compression for the material.

iv) Stresses are uniform across the width of the beam and do not exceed the limit of proportionality.

v) The cross section of the beam is symmetrical about the plane of bending.

vi) A transverse section of the beam which is plane before bending remains plane after bending.

vii) Every longitudinal fibre is assumed to be free to extend or contract without being restrained by its neighbours.

The beams of interest to this study (plant stems) will not conform exactly to this set of assumptions, though

they are often sufficiently close to allow the theory to be used. Consider a beam bent by a moment, (M), as shown in figure 1.3.

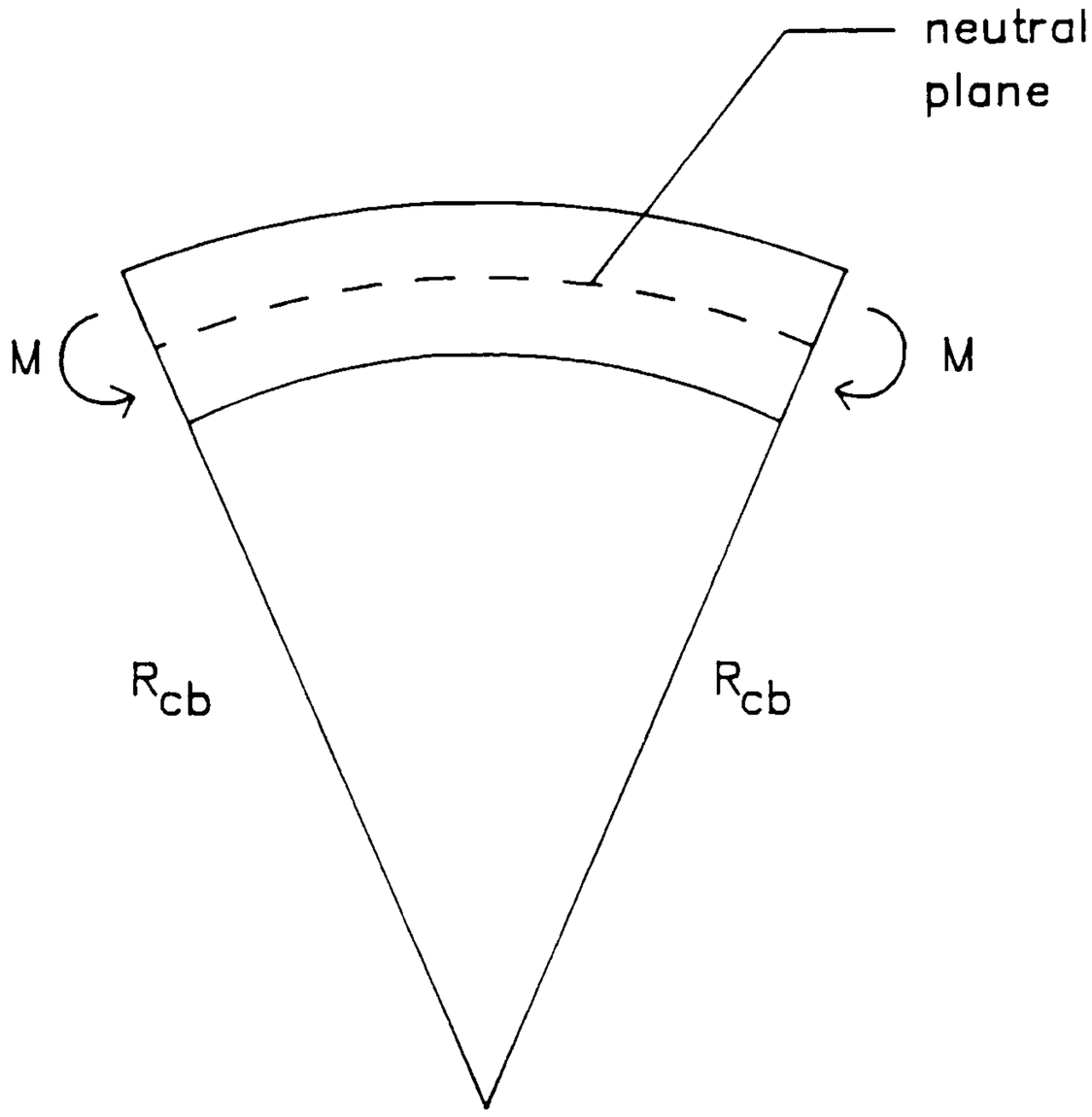


Figure 1.3 Bending of a beam due to a moment (M). Tensile strain is present in the upper half of the beam, and compressive strain in the lower half. Between the two is the neutral plane in which there is no strain. (R_{cb}) is the radius of curvature of the neutral plane.

The curvature of the beam is related to (M) in the equation;

$$\frac{M}{I_g} = \frac{Y}{R_{cb}} \qquad 1.1$$

Hence as (M) is increased (R_{cb}) decreases, or, in other words the beam bends more. Rewriting equation 1.1 it is

clear that, for a given moment acting on the beam, (R_{cb}) is greater (and thus the amount of bending in the beam less) the higher the value of the flexural rigidity, ($Y.I_g$);

$$M.R_{cb} = Y.I_g$$

Using equation 1.1 it is possible to derive further equations to describe the deflection of beams due to a variety of loading and end fixation conditions. These are covered elsewhere, in textbooks on the strength of materials (eg. Den Hartog, 1949; Polakowski and Ripling, 1966; Stephens, 1970).

One area where the theory of bending is particularly useful is in the determination of (Y) for materials where accurate measurement of the extension under load (as in figures 1.1 and 1.2) is not possible due to it either being very small, or due to difficulties in applying a load to soft biological materials without causing damage. Such an approach is used in chapter 2, below.

Oda *et al* (1966) summarised the factors contributing to lodging in cereal crops. Wind and rain displace the heads of plants creating a bending moment in the stem. Additional torque arises in the stem from this displacement, its magnitude depending both on the length of the stem and the weight of the upper parts of the plant. The resulting bending moment is opposed by the

resistive bending moment of the stem (arising from its elasticity, stiffness, and cross-section) and the resistance offered by the roots. When a critical bending moment is reached failure will occur either through stem fracture or uprooting.

Alexander (1971) gives a simplified illustration of wind acting on a tree. The tree is treated as a simple cantilever (a beam fixed at one end and free at the other) and beam theory is applied (see figure 1.4). The bending moment (M) resulting from a drag force (F_1) acting at a height (z) is found from the elementary relationship

$$M = F_1 . z \qquad 1.2$$

The maximum stress, (σ) in the trunk resulting from this moment is then

$$\sigma = \frac{F_1 . z . R}{I_g} \qquad 1.3$$

where R = radius of trunk

Alexander goes on to show that the minimum radius (R_{min}) to ensure that failure will not occur through fracture of the stem can (in theory) be calculated from

$$R_{min}^3 = \frac{4 . F_1 . z}{\pi . \sigma} \qquad 1.4$$

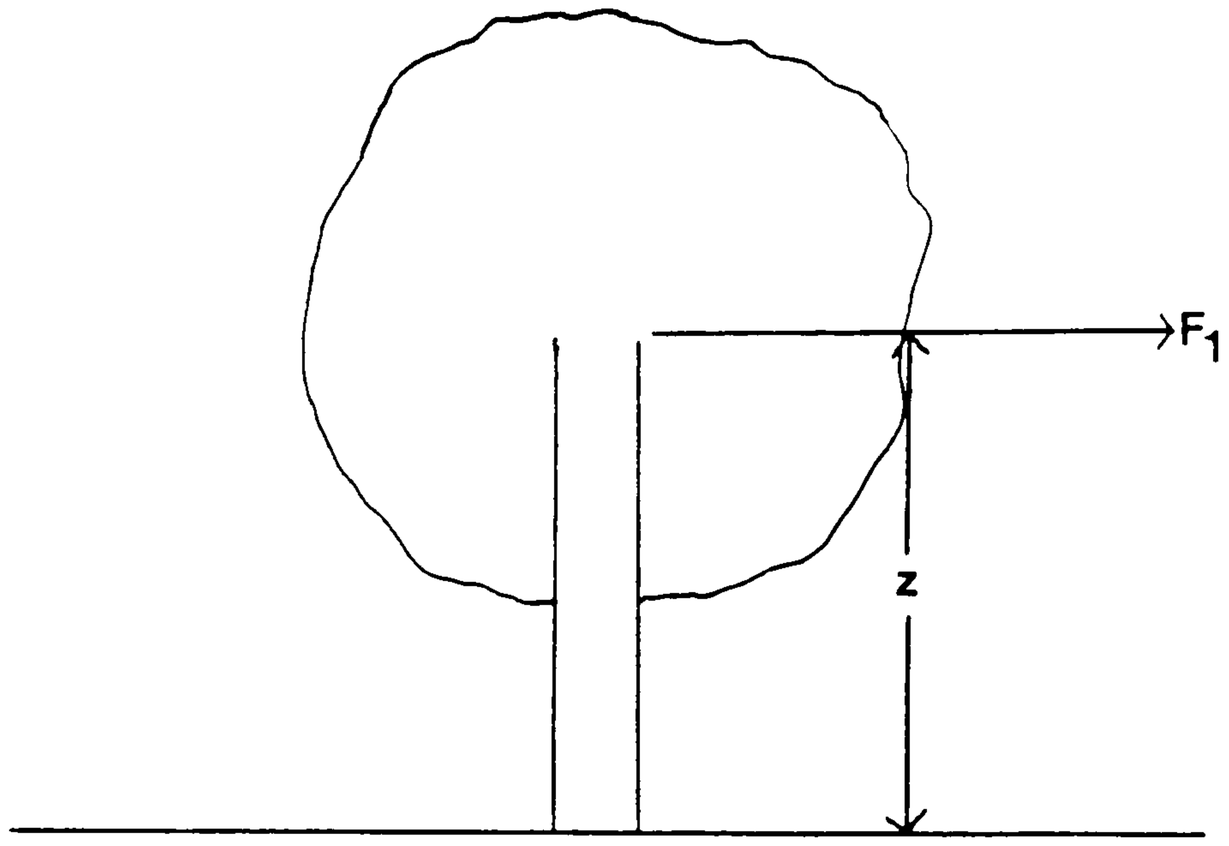


Figure 1.4 Model of wind action on a tree from Alexander (1971).

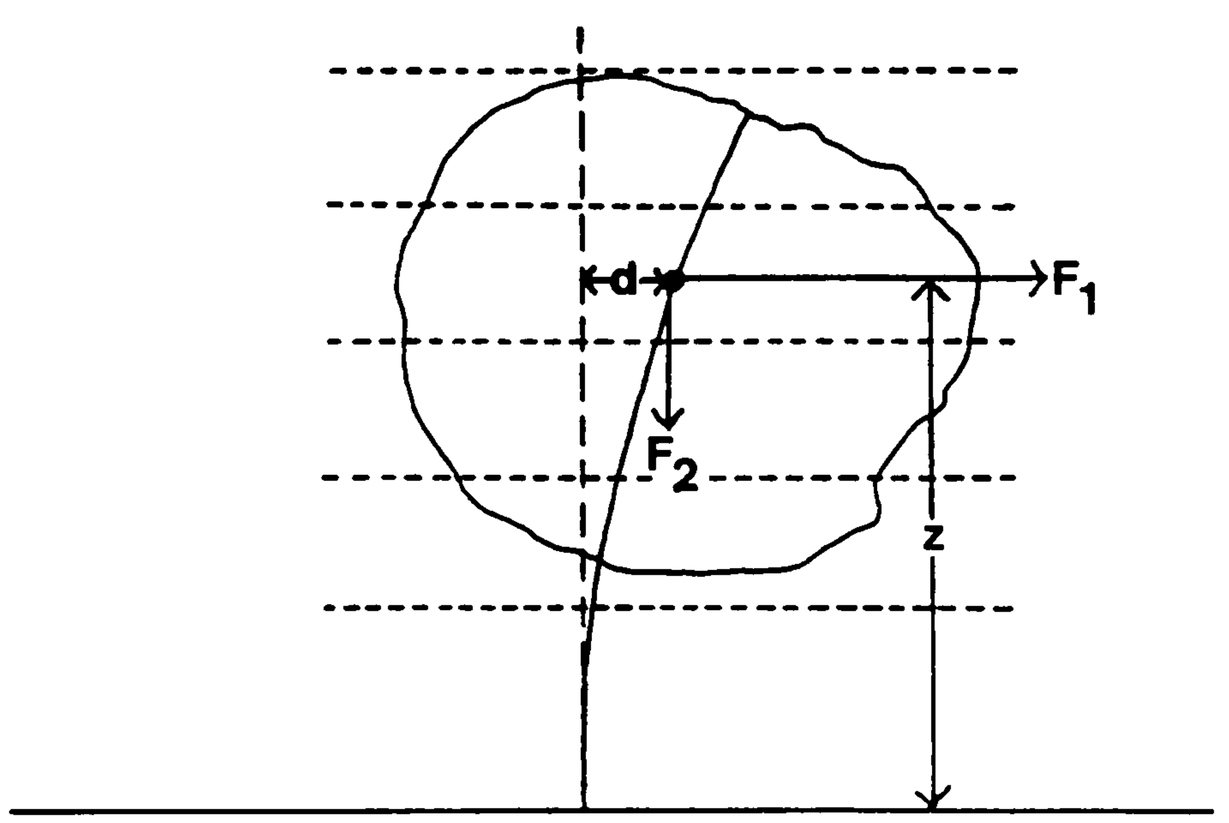


Figure 1.5 Model of wind action on a tree from Grace (1977).

Grace (1977, p120) also considers the action of wind upon trees (figure 1.5). The crown is divided into a series of layers, and the drag force (F_1) acting on each layer is found from the equation:

$$F_1 = \rho.C_d(z).u(z)^2.A(z) \qquad 1.5$$

where ρ = density of air
$C_d(z)$ = canopy drag coefficient at a height (z)
$u(z)$ = windspeed at height (z)
$A(z)$ = area of crown at height (z)

The contribution of the forces acting at each level to the total moment about the base of the stem is found by applying equation 1.2. Deflection of the crown produces a second moment (M_2) due to the mass (m) of the canopy, where, for each layer that the canopy is divided into (M_2) is calculated as

$$M_2(z) = m(z).g.d(z) = F_2(z).d(z) \qquad 1.6$$

The total moment is then found by adding together all the values for (M_1) and (M_2) from the series of layers that the canopy was divided into. Jones (1983) deals with the subject in a similar manner to Grace, though additionally incorporates the torque due to rainfall by treating the interception of rain as a momentum flux acting at the top of the canopy.

Petty and Swain (1984) used modelling techniques to investigate factors influencing stem breakage of conifers in high winds, taking into account the variation in wind-speed and crown distribution through

the canopy. The critical wind-speeds for lodging were in the range 20 to 40 m s^{-1} for trees 16 m tall and of varying taper, in accordance with the predictions of the Windthrow Hazard Classification (Booth, 1977).

Attempts have been made to measure the torque necessary for lodging directly, as in the tree pulling experiments of Oliver and Mayhead (1974), Fraser and Gardiner (1967), and Coutts (1986), and the wind tunnel study on rice by Tani (1963). Oliver and Mayhead forecast that a wind-speed of 40 to 45 m s^{-1} at the centre of pressure would be necessary to cause lodging in Sitka spruce. Fraser and Gardiner calculated that speeds in excess of 20 m s^{-1} were required on unstable soils. However, during a destructive gale in which trees were blown down, Oliver and Mayhead (1974) found peak gusts at the top of the canopy of only 17 m s^{-1}, whilst 5 minute average values at the centre of pressure did not exceed 3.5 m s^{-1}. Similarly large discrepancies between results from laboratory investigations and observations from the field were reported by Tani (1963), studying lodging in cereals. In the laboratory a torque of 0.2 N m about the base of the stem was required to give stem fracture, whilst in the field a torque of only 0.056 N m was necessary. Monteith (1973) ascribes such differences to three possible factors:

i) High speed gusts of wind.

ii) Resonance between plants and the dominant period

of passing eddies.

iii) Weakening of plants by disease.

Milne (1986) showed the importance of the difference between static loading (ie. due to a constant wind-speed) and dynamic loading (ie. due to a fluctuating wind-speed) on the moment applied to a tree stem. Milne estimates that wind gusting at the natural sway frequency of a tree may be as much as five times more effective than a load applied statically. Such an effect is clearly large enough to account for the discrepancy reported by Tani (1963).

The successive passage of eddies over a canopy can also cause vibration in plants (Inoue, 1955) especially when the dominant period of eddies coincides with the resonant frequency of the stems. This may loosen the rootplate and increase the chance of uprooting (Hutte, 1968; Coutts, 1986). Damping of the motion of Sitka spruce trees by neighbouring plants was investigated by White *et al* (1976) who found that much energy was dissipated through tree to tree contact.

The two types of lodging found in cereals and trees, stem breakage and uprooting, are illustrated in plates I and II. Of the two uprooting is by far the commonest for both cereals and trees (Neustein, 1971; Pinthus, 1973). Grafius *et al* (1955) found stem failure in cereals only occurred in plants that were diseased or

Plate I Trunk of a large beech tree snapped during the destructive storm which swept over southern England in October 1987, taken a month later. The trunk was badly decayed inside. Fruiting bodies of the fungus *Galerina mutabilis* may be seen (arrowed). This species is saprophytic as opposed to parasitic, and hence was not responsible for the original decay of the stem that led to wind-snap.

Plate II A beech tree uprooted during the severe storm of October, 1987, in southern England.

senescent after ripening. Udagowa and Oda (1967) found wind-speeds of 30 m s^{-1} were capable of lodging wheat and barley, though this was unlikely to occur through stem breakage if the culm was moist and turgid. Water (from rain or irrigation) can make uprooting more likely by disturbance of the soil-root interface. Pinthus (1973) demonstrated a 50% reduction in the critical torque for uprooting after watering.

Inspection of pea plants and pea crops reveals significant differences to cereals or trees in their standing ability. The presence of tendrils allows wild pea plants to remain erect by clinging onto surrounding plants rather than by virtue of possessing a strong stem. When grown singly or in small groups pea plants are incapable of supporting themselves even in the sheltered conditions of a greenhouse. When grown together as a crop the plants will fall over when only a few centimetres tall. However, once plants are large enough to cling on to other plants with their tendrils, the crop stands fairly well. The 'design' of the canopy in mid-season can be likened to that of a building in which the low bending strength (at least over long distances) of the individual columns of the structure is overcome by connecting columns together with horizontal beams to make a rigid framework. In the last few weeks of the season, the filling of pods in the upper canopy and drying of the stem from the ground upwards

destabilises the canopy and causes collapse. Unlike forest or cereal crops, where small areas of lodged plants may be found, perhaps traceable to some topographical feature (Neustein, 1971), or due to disease operating at a localised level, all plants in a pea crop collapse together as a matter of course rather than as a rare event, bearing a greater correlation to developmental stage than to wind-speed or rain. A fourth important difference is that uprooting is not found, collapse being solely due to failure of the canopy structure (the framework formed by the linking of stems through petioles and tendrils).

Given these differences, it is clear that analysis of standing in pea crops must be treated in a different manner to standing ability of other crops where there is much less mutual interaction and lodging is not so common. The crop cannot be treated as if it is composed of a number of (more or less) isolated cantilevers, in a similar manner to the models of Alexander (1971), Grace (1977), and Jones (1983). Given the inability of pea plants to support themselves when grown in small groups, it seems possible that the mechanism of lodging may be different in peas. Whilst lodging occurs in other species through the bending moment acting on the stem exceeding a critical value, it is possible that pea

canopies may collapse as a result of the compressive load on the stems at the bottom of the canopy exceeding a critical value, (P_E) forcing the stems to buckle.

The theory of buckling originated in 1744 when Leonard Euler, taking the case of a perfectly elastic pin-jointed column (see below), published the equation;

$$P_E = \frac{\pi^2 . Y . I_g}{l^2} \qquad 1.7$$

where l = the length of a pin-jointed column

Euler's theory makes the following assumptions:

i) The column is initially straight.

ii) The load is applied axially.

iii) The material is homogeneous.

A column meeting these assumptions will not buckle under the load (P_E) unless disturbed. For practical purposes the disturbance may be provided by some kind of imperfection in the column or through the load being applied slightly off-axis.

It is evident from equation 1.7 that whilst the value of (P_E) is dependent upon ($Y.I_g$), it is independent of the strength of the material, as the yield stress and ultimate stress (see figure 1.2) are not included in the equation.

(P_E) is, however, heavily dependent on the manner in which the ends of the sample are fixed (see Gero and Cowan, 1976, p. 227). There are three types of fixation; pin-jointed (free to rotate about the point of fixation); fixed (unable to rotate); and free (unconnected). In practice it should be noted that ideal pin-joints and fixed ends are hard to achieve. To incorporate these different types of end fixity in equation 1.7 without changing the value of (P_E) for samples of a given material of given cross section, it is necessary to substitute the effective length, (l_E), for (l) in equation 1.7. This is a simple matter, performed using the relationships shown in table 1.2.

Table 1.2 The relationship between the effective length of a column (l_E) and the measured length (l) in Euler's formula (equation 1.7) for different types of end support.

Both ends pin-jointed	$l_E^2 = 1.l^2$
One end pinned, one end fixed	$l_E^2 = 0.5.l^2$
One end fixed, one end free	$l_E^2 = 4.l^2$
Both ends fixed	$l_E^2 = 0.25.l^2$

A further complicating matter in the subject of buckling is the existence of a series of higher buckling modes, as shown in figure 1.6, along with associated values of (P_E). These modes will only develop if some kind of

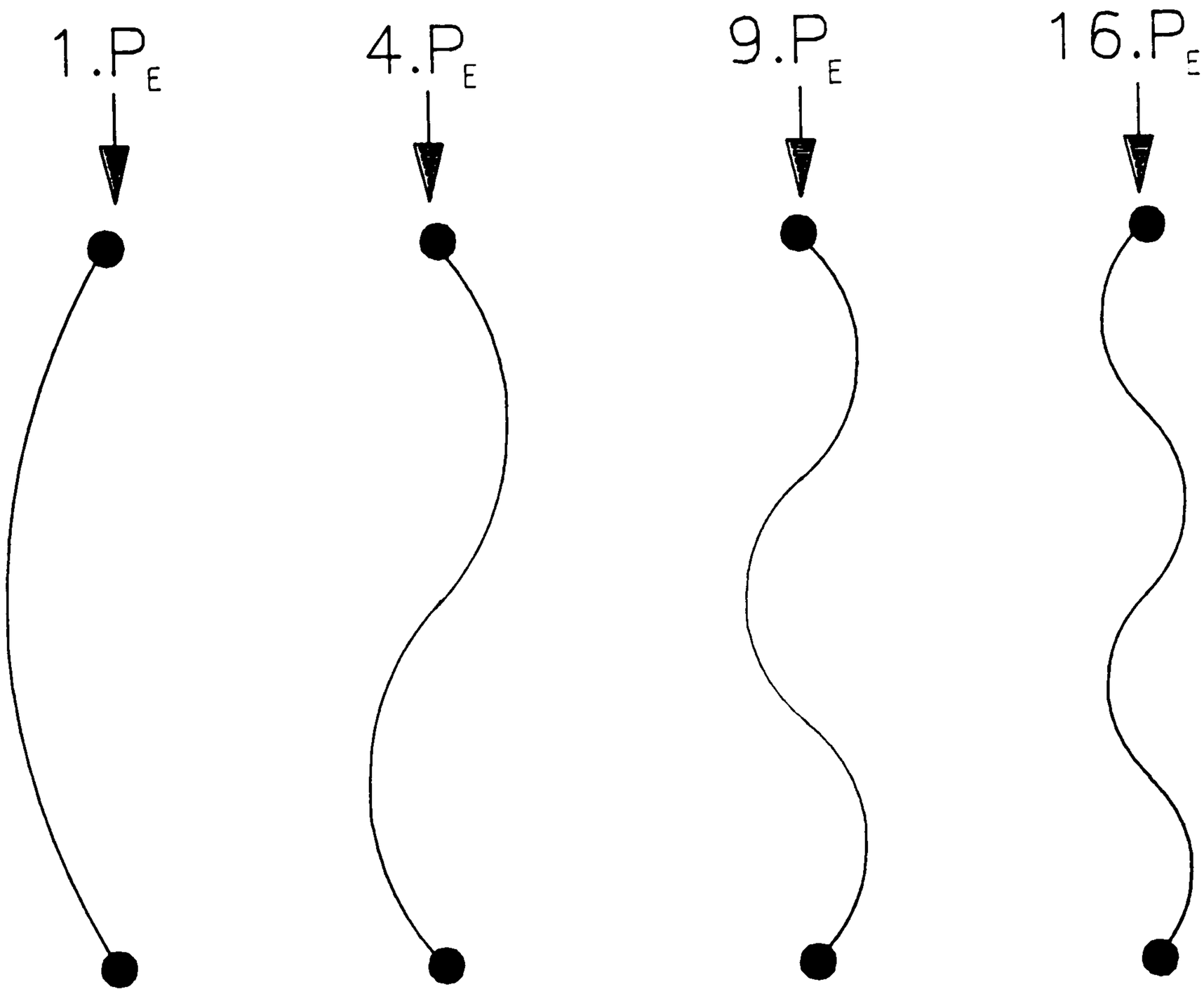


Figure 1.6 Modes of buckling in pin-jointed columns and associated loads (relative to the Euler load, P_E). It should be noted that the higher modes (n > 1) will only develop if lateral support is given. For most practical cases only mode 1 need be considered. The number of possible modes is limited to the point where failure will occur in the outer fibres of the stem due to a combination of buckling and overstressing.

lateral support is provided.

Several other formulae are available to cope with cases where Euler's equation (1.7) is not quite suitable. Whilst failure in a long column will occur through buckling, very short columns will fail due to direct compression. The Rankine formula is used for columns of intermediate length where failure is due to a combination of buckling and overstressing. To account for cases where the column is intially curved, or the load is applied off-axis, the Perry formula and the secant formula, respectively, are available. These relationships are included in the reviews of buckling given in the texts by Stephens (1970), Gero and Cowan (1976), Collins (1981), and others.

It is worth considering what approaches may be used to improve standing ability of the crop, and which seem most likely to give beneficial results. The following suggestions are made on ways of either preventing canopy collapse entirely or delaying it to reduce the length of time that plants spend lying on the ground under unfavourable conditions.

i) Providing artificial support.

This is probably the most obvious solution, having been successfully employed with other crops (eg. soybeans and hops), and would certainly work. However, the costs of

labour and materials would negate any benefits arising from improved yield. Artificial supporting elements would also interfere with the harvesting machinery.

ii) The use of 'nurse' crops.

As peas and their close relatives have evolved to rely on other plants for support, several workers have tried growing mixtures of peas with plants with better standing ability. Similar techniques have previously been successfully used with mixtures of cereals (Pinthus, 1973). Murphy (1983) reported improved yield in comparison to controls for mixtures of oats and peas. However, yields in this experiment were low (ranging from only 0.4 to 1.8 t/ha in controls), and questions must be asked as to whether the improvement in yield would still be seen if crops were grown under better conditions and hence an increased level of competition. More recently Lovelidge (1987) has reported an increased yield of about 50% for peas grown with spring barley (sown at low density) for several growers in the south-western counties of England in 1986. Success has also been reported by farmers using this method in 1987 (Anon., 1988). Snoad (1983) stated that the use of leafless peas to improve standing in mixture with conventional pea plants is unlikely to prove beneficial as the reduced growth rate of leafless varieties (Hedley

and Ambrose, 1981) makes them poorly competitive and hence unlikely to survive for very long in the population.

iii) Autumn sown crops.

These crops are ready for harvest about two weeks before spring sown varieties. Proctor (1963) showed that conditions at harvest for spring sown crops (early August) are significantly wetter than during the last fortnight of July in the areas of the United Kingdom most suited to growing peas. Cousin (1976) found that winter hardy crops yielded 40% higher than other varieties due to increased leaf area duration. Unfortunately, however, the problems involved in developing crops that could survive the winter in Northern European climates are manifold (Snoad, 1983).

iv) Breeding for increased stem stiffness and strength.

The greatest improvements with respect to these characteristics have so far been found in fasciated mutants in which the stem is stiffenned through multiplication of the vascular bundles, and in tare-leaved rogue varieties in which leaves and stipules are smaller than normal, and stems are stiffer. Unfortunately, in both cases, undesirable characteristics are carried over with the improvement in stem strength (eg. increased seed abortion and unusual inheritance patterns) which make these varieties

unsuitable for use in the breeding programme. Some improvement has been found in other varieties (eg. Sentinel) with no undesirable characteristics, though to a much lesser degree.

v) Breeding for other characteristics.

Most success in improving standing ability has been found in the leafless mutants in which stipules are reduced to vestigial organs and leaflets are converted to tendrils (see plates III and IV). Snoad (1980, see table 1.1) found losses through staining of seed greatly reduced for such a variety (Filby) in comparison with conventional plants. Semileafless mutants have also been bred, in which leaflets are again converted to tendrils though stipules are the same size as in conventional plants (see plates III and IV). Leafless varieties are capable of standing throughout the season until harvest (Snoad and Hedley, 1981). Kielpinski (1981) found in trials in Poland that plants possessing the afila gene (the gene that governs the presence of leaflets or their conversion to tendrils) remained upright 5 to 15 days longer than others and did not lodge as badly. However, due to a reduction in photosynthetic area, and hence a reduction in the total amount of light intercepted by the crop (Mackerron and Thompson, 1983), yield can be reduced by as much as 30

Plate III Leaves from pea plants of differing leaf morphology. From left to right: leaves from a conventional plant, a semileafless plant, and a leafless plant.

Plate IV Pea plants with contrasting leaf morphology. From left to right: the varieties Filby (leafless), Filigreen (semileafless), and Birte (conventional). These varieties were amongst those used in the work described below.

or 40% (PGRO, 1984 b). Semileafless varieties generally yield as well as conventional varieties though standing ability does not seem to be significantly improved.

vi) The use of growth regulators.

The two factors which most improved standing ability in cereals were the breeding of varieties with shorter stems and the use of growth regulators, particularly 2-chloroethyl-trimethylammonium chloride (CCC). Cathey (1964) reported that CCC retards cell division and elongation in the sub-apical meristem of cereals. This leads to increased wall thickness and culm diameter, and reduced internodal length (Pinthus, 1973) giving plants that are both shorter and stronger. Heath and Hebblethwaite (1985 b), have reported some reduction in staining through the use of giberellic acid (as GA3), which produced plants 30% taller than controls. The improvement resulted from pods being held higher above the ground after lodging than in untreated plants. Possible benefits may, however, be minimal once the cost of application has been considered. Other growth regulators tested were found to depress growth and did not improve standing ability.

It thus appears that the most promising approaches for the improvement of pea crop standing ability are by the production of varieties with stronger stems or altered canopy morphology through the breeding programme, and by

using nurse crops. Given that the interactions between different crop species (or varieties) will be dependent on growing conditions (with reference to both climate and site), it is clearly preferable that varieties with improved standing ability be developed by breeders. Also, the use of nurse crops such as barley may reduce the suitability of dried peas as a break crop, allowing the perpetuation of serious diseases like take-all. Even if it is impractical to develop varieties capable of standing on their own, any improvement achieved by breeders will benefit the nurse crop approach.

The work presented below has been performed to improve understanding of the forces acting on the crop that induce lodging, and how these forces are opposed. Measurements have been taken using conventional, semileafless, and leafless phenotypes and varieties exhibiting increased stem strength. Canopy structure is investigated in chapter 2 using field crops and microplots. The influence of wind is considered in chapter 3 from wind profiles taken over crops throughout the season, and in chapter 4 through the measurement of the drag exerted on isolated canopy elements in the wind tunnel of the Department of Forestry and Natural Resources in Edinburgh. The effect of rain is studied both in terms of the additional loading of the crop due to the wetting of leaves and due to the absorption of momentum from intercepted rain drops. The results are

brought together in chapter 5 to present a unified picture of the stresses acting on dried pea crops. Conclusions, and implications for the breeding programme are presented in the final chapter.

CHAPTER 2

CANOPY STRUCTURE OF PEA CROPS

INTRODUCTION

Little attention has been paid to the structure of pea canopies in spite of the relevance of such work to the problem of lodging. This seems especially surprising with respect to stem structure and strength (Snoad, 1980). Available reports are mostly in the context of other work; MacKerron and Thompson (1983), for example, give the distribution of leaf area with height for conventional and leafless crops in a study of light interception. Even the dramatic alterations to the crop by the introduction of the leafless and semileafless phenotypes were originally intended to allow quicker processing of fresh peas by farm machinery, with the improvement in standing ability as a useful bonus (Snoad, 1974).

For a breeding programme to produce plants with improved standing it is essential that a better understanding of canopy structure is attained. The good use to which such information can be put has, of course, been demonstrated for wheat, barley and other cereals where crop stability was greatly improved by reducing the length of stem and by increasing stem strength (Austin *et al*, 1980). Whilst

structural analysis of cereals has concentrated on the mechanical attributes of the stem (eg. Grafius, 1958; Tani, 1963; Oda *et al*, 1966), models of tree stability have also included distributions of leaf area and mass with height (eg. Coutts, 1986; Milne, 1986). Consideration has also been given to the interactions between neighbouring trees (White *et al*, 1976).

From chapter 1 it is evident that, to be able to describe the effect that a given force or set of forces may have upon the pea crop, it is necessary to measure the values of (I_g), (Y), and (M_{max}) for pea stems and petioles at the time when lodging occurs. Measurements must be made on fresh material as these three parameters will all be affected by the water content of the samples under examination.

Other information required before a model of standing ability can be constructed includes detailed observations on the mechanism by which the canopy collapses. At this stage it is unclear whether lodging occurs in the same way as in other crops, or by a different mechanism, such as buckling. If the process is the same as that seen in trees and cereals then measurements of the distribution of plant fresh mass, crop area, and canopy components (leaves, pods, etc.) with height are also essential. Such measurements remain desirable even if the mechanism is

different as they may allow conclusions to be drawn on ways in which canopies may be re-designed to give better standing ability.

Given that pea stems and petioles approximate in cross section to hollow cylinders, (I_g) may be calculated as:

$$I_g = \frac{\pi}{4} (R^4 - r^4) \qquad 2.1$$

where

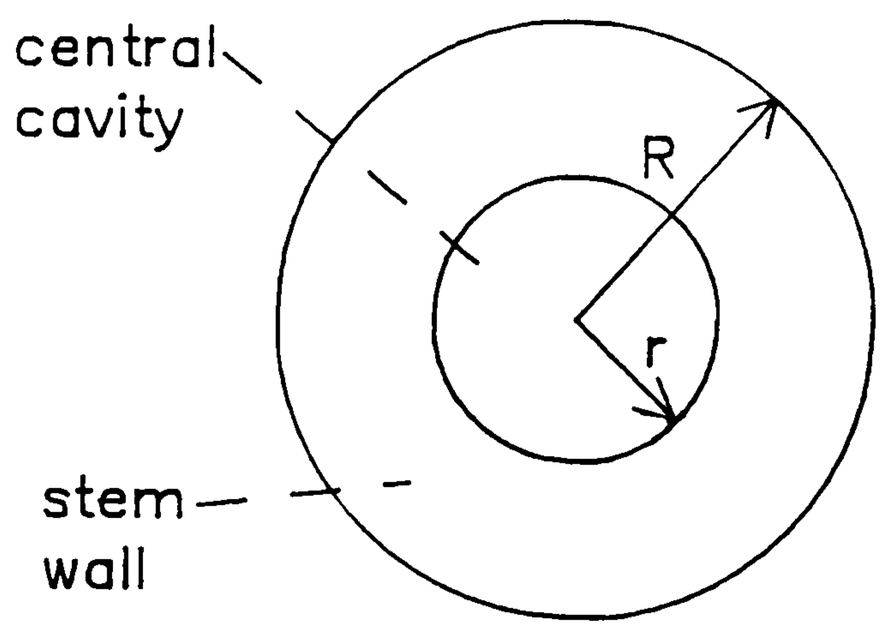


Figure 2.1 Definition of (R) and (r) for calculation of (I_g)

It has already been stated (in chapter 1) that it is often not possible to measure (Y) of soft biological materials (like pea stems and petioles) using methods whereby samples are placed under direct tension, as samples may be easily damaged and the extension under load may be too

small to measure accurately. Fortunately, relationships based on the theory of bending (see equation 1.1), and subject to the same assumptions, are available to relate (Y) to the deflection of beams under load (see Stephens, 1970). For a cantilever with load concentrated at the free end, the deflection (D) of the free end of the beam is given by:

$$D = \frac{P.l^3}{3.Y.I_g} \qquad 2.2$$

where

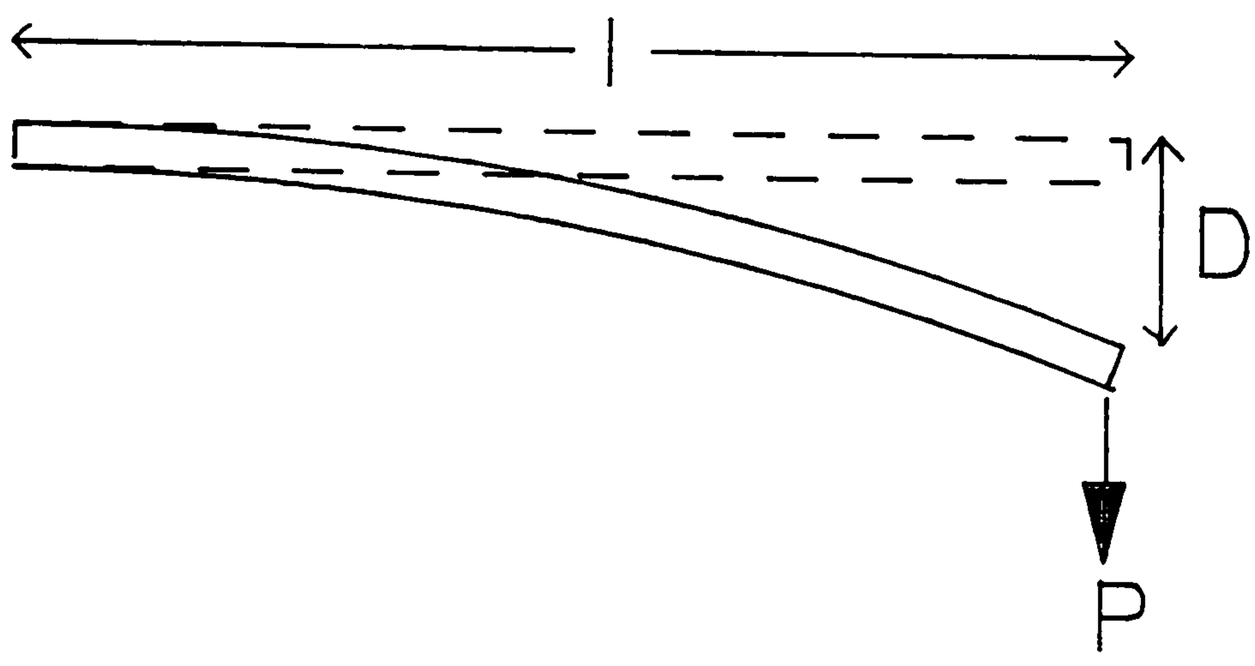


Figure 2.2 Definition of parameters for the calculation of (Y).

The derivation of this relationship and others dealing with the deflection of beams require that the deflection

is small in comparison to the length of the beam. Morgan and Cannell (1988) show that the theory only accounts for deflections not greater than 25% of a beam's length. It is unfortunate that some biological texts dealing with this subject (eg. White, 1974), do not mention the limitations of relationships like equation 2.2.

MATERIALS AND METHODS

Field Work

Field work was carried out at the Norfolk Agricultural Station, Morley St. Botolph, Norfolk. Plants were sown in mid-March 1984, and sprayed with Dinoseb (a post-emergence broad leaved herbicide), Hostathion (an organophosphorus insecticide to control pea moth and weevils), and Aphox (a carbamate insecticide to control aphids) as necessary during the season. The field plan is shown in figure 2.3, and the individual plots are described below. Climatic data (mean, maximum and minimum temperatures, rainfall and sunshine hours) are presented in appendix I. Mean temperatures were close to monthly norms for the area. Rainfall from early April to late May was very low, though the monthly total for June was almost twice the average due to a heavy thunderstorm on June 20th.

Field plots

These plots were used both for the canopy structure work

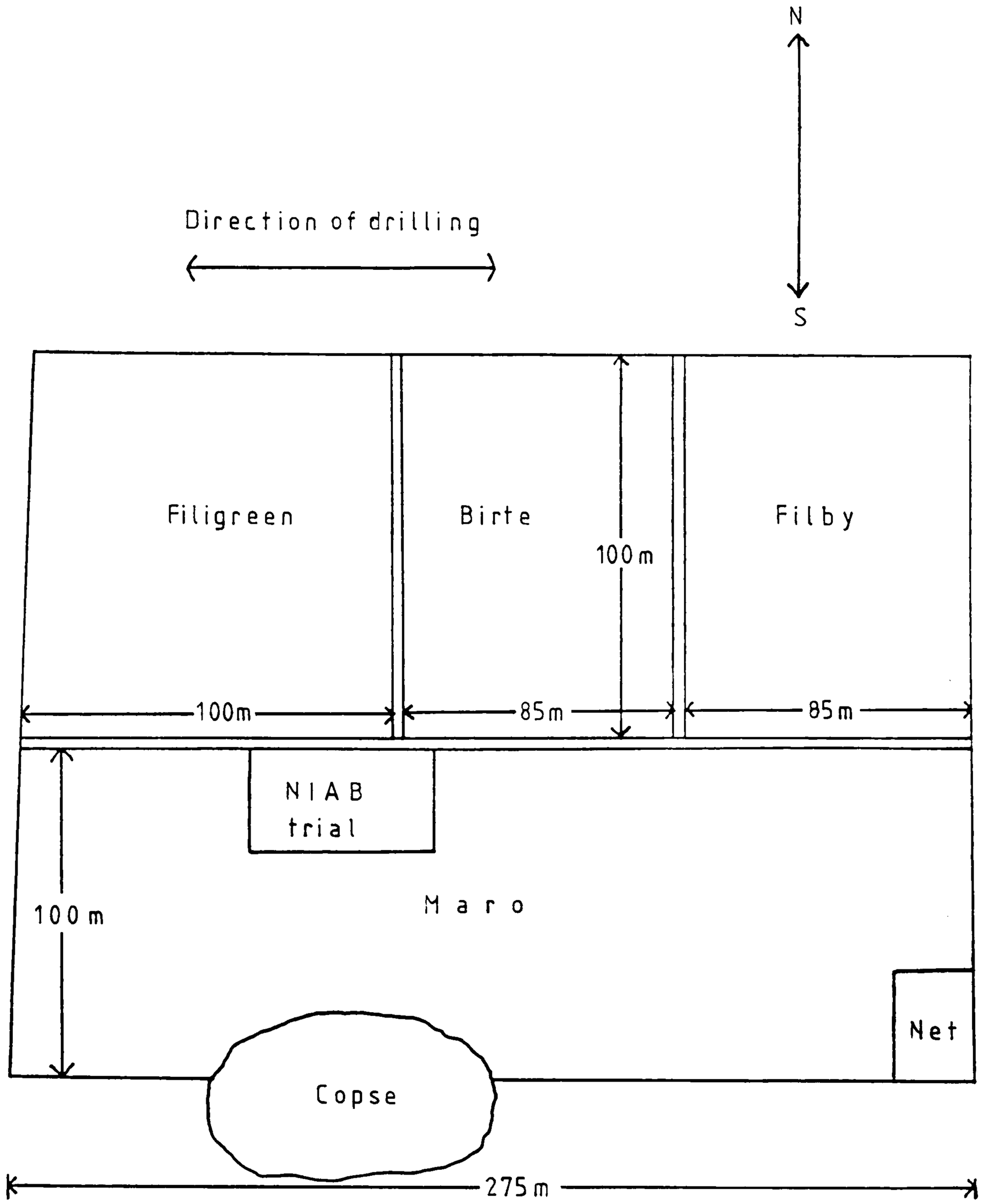


Figure 2.3 Field plan for the Norfolk Agricultural Station, Morley, Norfolk, in 1984. Plots of the varieties Maro, Birte (conventionals), Filigreen (semileafless) and Filby (leafless) are shown, with the NIAB trial plots and netted area containing microplots.

described in this chapter, and the wind profile studies of chapter 3. The three plots in the northern half of the field each measured approximately 85 m by 100 m and were sown with the varieties Filigreen (semileafless), Birte (conventional), and Filby (leafless) at measured densities of 105, 68, and 98 plants/m^2 respectively. Due to faulty sowing equipment the central plot (containing Birte) was not suitable for wind profile work as much of the canopy was poorly and unevenly formed, leaving insufficient fetch in all but a strictly north-south axis. This plot was replaced for the micrometeorological by the plot (80 m by 275 m) containing the conventional variety Maro at 68 plants/m^2. Canopy height and dry mass of randomly selected plants were measured in all four plots throughout the season. Relative growth rates (RGR) were calculated from the equation

$$RGR = \frac{\ln(W_2) - \ln(W_1)}{t_2 - t_1} \qquad 2.3$$

where W_1 and W_2 = dry mass at time 1 (t_1) and time 2 (t_2) respectively.

Three subplots (each approximately 1.5 m square) were randomly selected in each of the four field plots. Just before lodging was expected the plants within these subplots were given additional support in the form of a network of twine suspended from posts sited at the corners of each subplot to prevent their collapse, in order that the structure of the canopy at lodging be accurately measured. When height measurements of the surrounding

plants showed that collapse had started, the central 25 plants of each subplot were harvested. Measurements of the vertical distibution of fresh mass, crop area (the sum of pod, leaf and stem projected areas, measured with a Model AAM-7 area meter, Hayashi Denkoh Co. Ltd., Tokyo, Japan), and numbers of leaves, pods, and plant to plant connections were made by horizontally clipping strata at 15 cm intervals.

NIAB trial

A series of 32 plots (10 m by 2 m) containing 2 replicates of each of 16 varieties were precision sown at recommended densities (PGRO, 1984 a) for use by the National Institute of Agricultural Botany. Whilst these plots were not available for intensive canopy structure study, measurements of canopy height were taken weekly near the end of the season to identify those varieties with the best standing ability.

Microplots in the netted area

Microplots (each approximately 1.4 m square) were planted under the net in the south-eastern corner of the field. Plants were supported as they grew by netting stretched between iron posts driven into the ground at the corners of each microplot, replacing the support that would normally be given by neighbouring plants in a crop.

From the observations made on the NIAB trial plots and the growth of plants in the microplots three varieties were selected for study, Sentinel (semileafless), BS679 (tall, semileafless), and Progreta (tare-leaved rogue). All were sown at a density of 100 plants/m^2. Canopy structure was measured in the same manner as for the subplots from the field crops, through stratified clipping at 15 cm intervals (apart from BS679 which was so tall that a 20 cm interval was used). In each level the numbers of leaves and pods, and the fresh mass were measured. To eliminate errors due to edge effects only plants two or more rows in from the edge of the microplots were used.

Laboratory Work

Measurements of the structural attributes of stems and petioles were made on plants of the varieties Maro, Filigreen, Filby, Sentinel, and Progreta and of the cultivars JI1194 (conventional), JI1195 (semileafless), and JI1198 (leafless), the last three being genotypes from the near-isogenic series MISOG1. 10 plants of each variety were used for measuring (Y), (I_g) and (M_{max}). Measurements of the amount of water that could be carried on the surfaces of each of the three different leaf forms were made on leaves from a further 10 plants of the cultivars JI1194, JI1195, and JI1198.

Seeds were sown singly in 10 cm pots in the soil mix UCIID (Baker, 1969) in mid-March 1985. This soil mix is based

on a 3:1 mixture of peat and fine sand with nutrients added, and is recommended for general horticultural use. Plants were grown on under glass with a minimum temperature of 12°C, and watered as necessary (ie. when the soil surface was dry). Canes were used for support. Measurements were made on these plants in the last week in June and the first week in July when they had reached the stage where pods had filled and plants had begun drying out from the base upwards (this approximates to the stage when canopy collapse occurs in the field).

Main stems were marked at 10 cm intervals from the soil upwards. The uppermost 10 cm length of stem from each plant was cut off and used first, followed sequentially down the stem by the other lengths in order to avoid problems due to prolonged water loss. To measure (Y) these samples were held horizontally in a laboratory clamp with rounded, rubber sleeved jaws (see figure 2.4). A small carrier was hooked over the free end of the stem. Weights were then added with an increment of 1/2, 1, or 5 grams, depending upon the stiffness of the sample under test. Deflections (D) of the free end of each sample under each weight were measured to the nearest 1/2 millimetre using a firmly clamped ruler. After the addition of each new weight time was allowed for each sample to settle to its new position. The length of each sample (l) from the weight carrier to the point of attachment to the clamp was also measured with a ruler to the nearest millimetre.

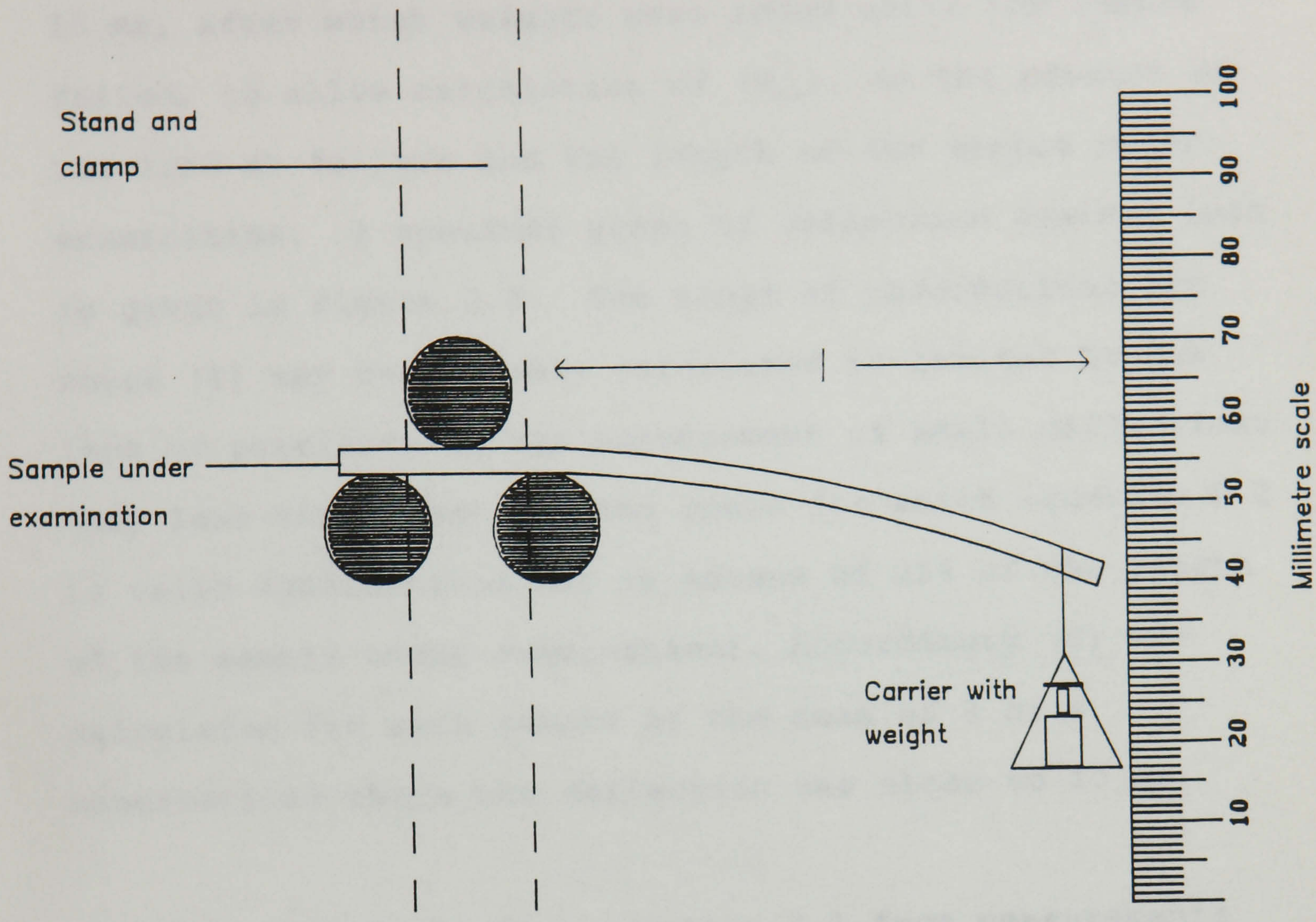


Figure 2.4 Measurement of the deflection (D) of a horizontally held sample of stem due to a load (P). Lengths of stem were held in the rounded rubber sleeved jaws of a laboratory clamp. For each 10 cm interval up the stem 10 samples were studied for each variety.

Readings were taken until the deflection exceeded about 15 mm, after which weights were added until the sample failed, to allow calculation of (M_{max}), as the product of the load at failure and the length of the sample under examination. A specimen graph of deflection against load is given in figure 2.5. The range of observations for which (Y) may be reliably calculated is limited by the lack of precision in the measurement of small deflections (say less than 5 mm) and the range for which equation 2.2 is valid (deflections not in excess of 25% of the length of the sample under examination). Accordingly (Y) was calculated for each sample as the mean of 3 or 4 observations where the deflection was close to 10 mm.

(I_g) was calculated from equation 2.1 from measurements made as follows. Each 10 cm sample used in the measurement of (Y) was cut into two equal parts. The external diameter of the sample (to allow calculation of R) was measured at each of the two newly cut ends with a pair of Vernier calipers to the nearest 0.1 mm. The thickness of the stem wall was then measured, and the radius of the central cavity (r) calculated from the subtraction of the wall thickness from (R). (I_g) was then calculated for each sample from the mean values of (R) and (r).

(Y), (M_{max}) and (I_g) of petioles were measured in a similar manner, though the petioles were held in a different way

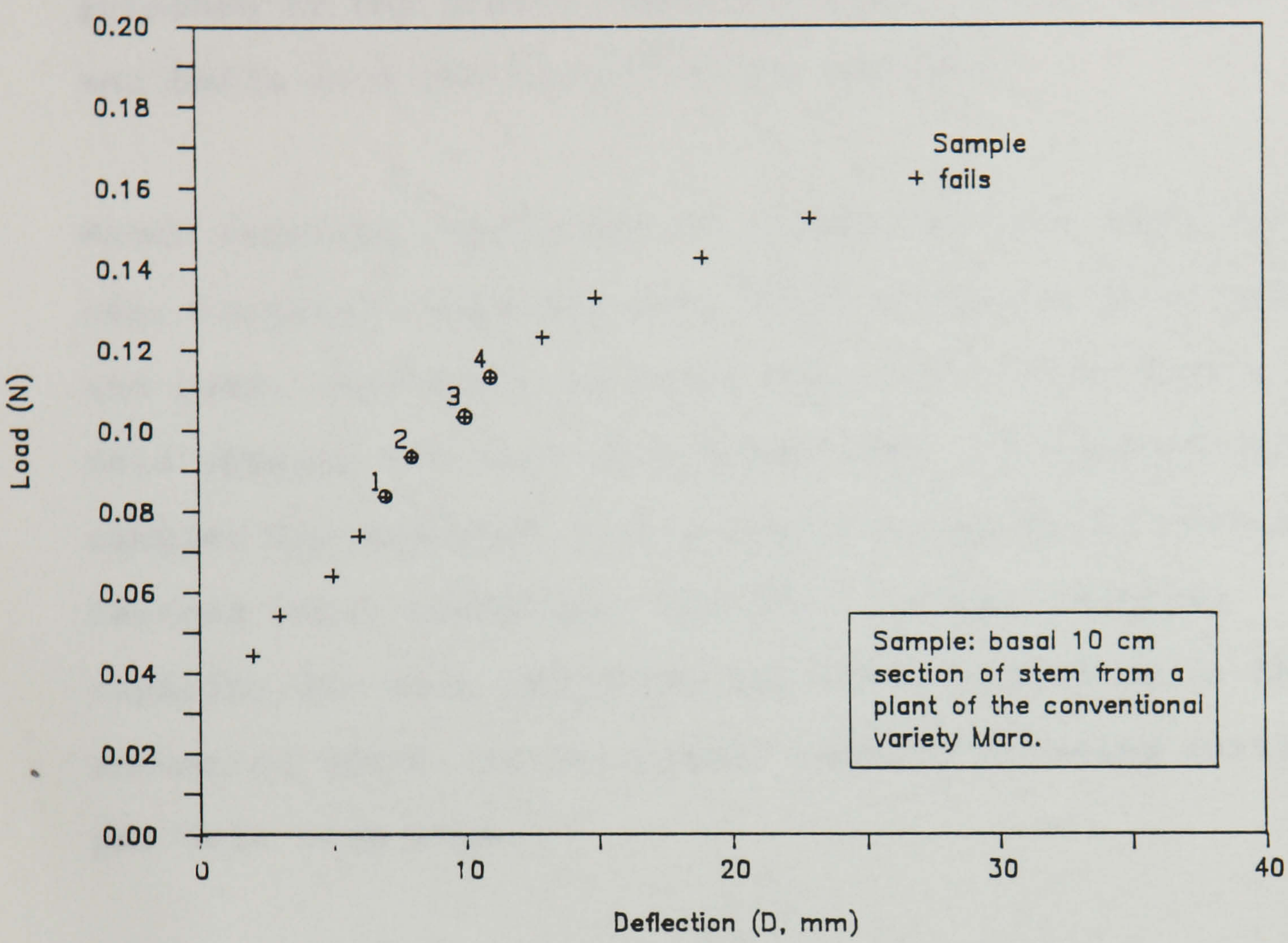


Figure 2.5 Deflection of a horizontally held sample of the stem of the leafless cv. JI1198 against a load (P) concentrated at the free end. (Y) was only calculated for the points marked ⊕ and given the numbers 1, 2, 3, and 4. In these cases deflections were both large enough to measure accurately, and small enough not to invalidate equation 2.2 (see text). From such data (Y) was calculated as follows:-

Rearranging equation 2.2:

$$Y = (P.l^3)/(3.I_g.D)$$

For the sample shown in this figure, l = 55 mm, I_g = 2.82 mm^4 For point 1 (D = 7 mm, load (P) = 0.084 N)

$$Y_1 = (0.083 \times (55)^3)/(3 \times 2.82 \times 7) = 236 \text{ N mm}^2$$

similarly for point 2

$$Y_2 = (0.093 \times (55)^3)/(3 \times 2.82 \times 8) = 230 \text{ N mm}^2$$

for point 3,

$$Y_3 = (0.104 \times (55)^3)/(3 \times 2.82 \times 10) = 204 \text{ N mm}^2$$

and for point 4,

$$Y_4 = (0.113 \times (55)^3)/(3 \times 2.82 \times 11) = 202 \text{ N mm}^2$$

Taking the mean of these four estimates,

$$Y = 218 \text{ N mm}^2$$

to the stems. Measurements were made with petioles still attached to the plants, with the stem firmly clamped above and below each petiole as it was studied.

Water carrying capacities of leaves and pods from the near-isogenic cultivars were measured by weighing leaves and pods, thoroughly spraying them with water from a hand held sprayer and then reweighing them. Projected area of samples was measured with a Delta-T area meter (Delta-T Devices Ltd., Cambridge, CB5 0EJ). Water carrying capacity for each phenotype was then calculated as the amount of water (in kilograms) capable of being carried per unit crop area.

RESULTS

Field plots

Growth of the varieties Maro, Birte, Filigreen and Filby over the season is shown in figure 2.6 for dry mass and figure 2.7 for canopy height. Differences in accumulation of dry mass for the conventional and non-conventional varieties are clear. Relative growth rates in the exponential phase are shown in table 2.1. The similarity between relative growth rates for this phase suggests that differences in final dry mass arise through faster growth just after germination by the conventional varieties (see also Pyke and Hedley, 1981).

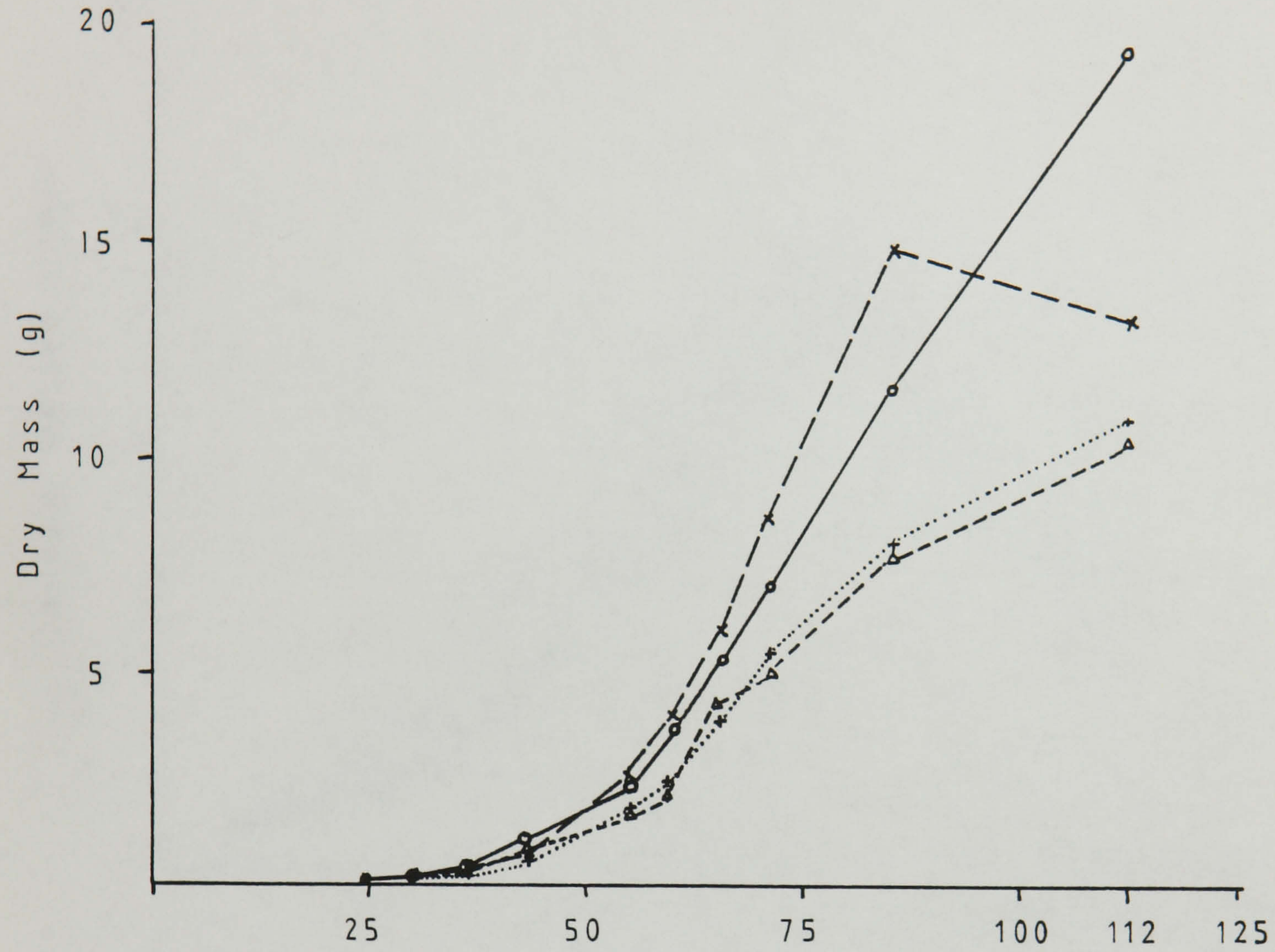


Figure 2.6 Dry mass growth per plant over the 1984 season for the varieties Maro (——o——), Birte (— — —x— — —), Filigreen (- - - - -△- - - - -), and Filby (·····+·····) from the field plots.

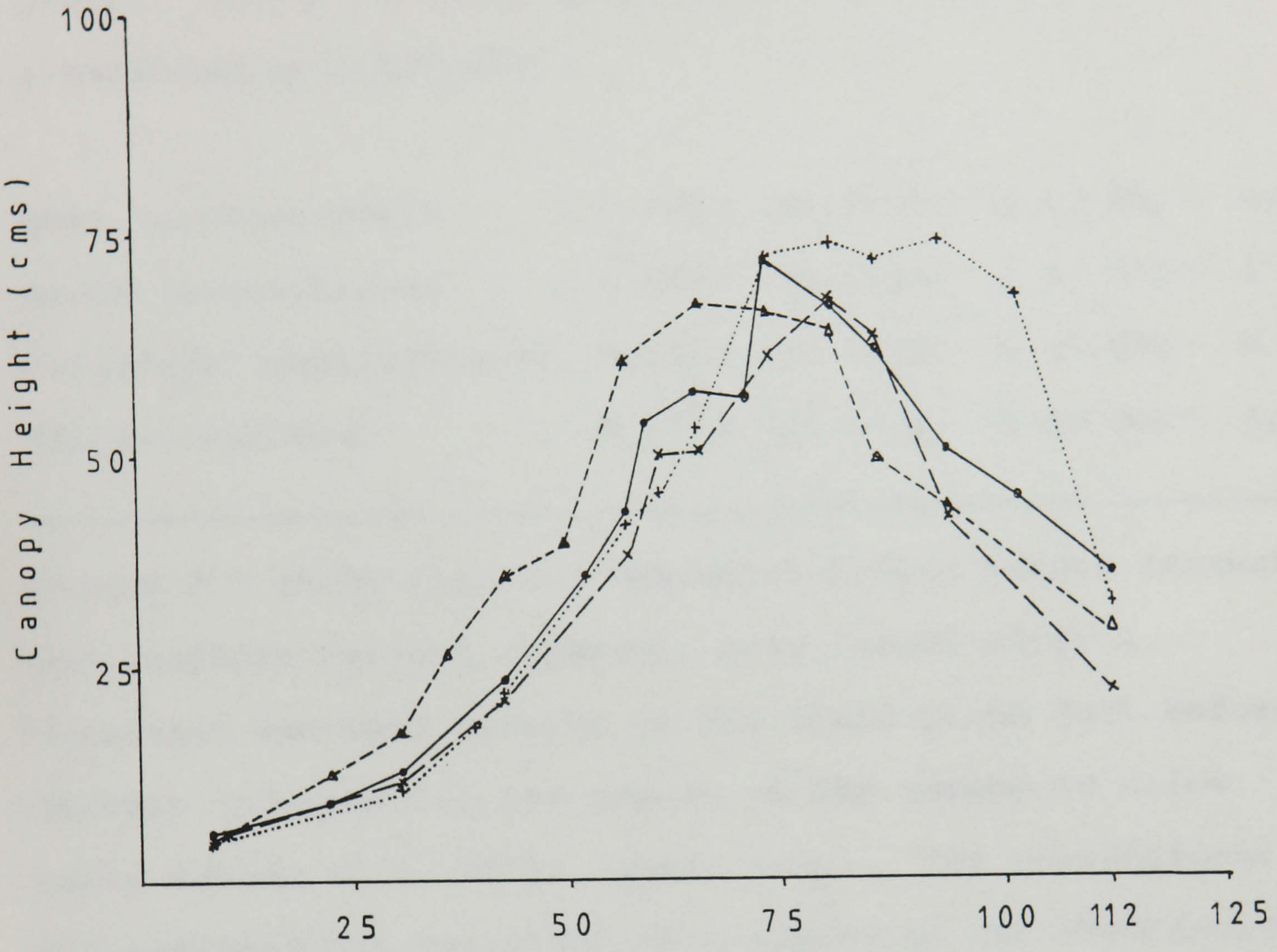


Figure 2.7 Change in canopy height during the 1984 season for the varieties Maro (——o——), Birte (– – –×– – –), Filigreen (-----Δ----), and Filby (·····+·····) from the field plots.

Table 2.1 Relative growth rates with standard error of regression coefficient calculated from equation 2.3 for the exponential phase of growth for varieties in the field plots. Values followed by the same letter are not significantly different.

Maro (conventional)	0.0717 (±0.0018)	g g^{-1} day^{-1}	a,b
Birte (conventional)	0.0769 (±0.0024)	g g^{-1} day^{-1}	a
Filigreen (semileafless)	0.0691 (±0.0024)	g g^{-1} day^{-1}	b
Filby (leafless)	0.0713 (±0.0012)	g g^{-1} day^{-1}	a,b

Figure 2.7 shows that all varieties lodged before harvest. The leafless variety, however, only lodged after a dessicant had been sprayed on the field plots just before harvest (to speed up the drying of the canopy to allow early sowing of a winter cereal crop). The conventional and semileafless varieties also lodged in the 1983 season though the leafless variety remained erect until harvest.

Final yields of dried peas from each plot are given in table 2.2:

Table 2.2 Yields from the field plots.

Maro (conventional)	1.42 t/ha
Birte (conventional)	1.09 t/ha
Filigreen (semileafless)	1.40 t/ha
Filby (leafless)	1.63 t/ha

Observations through the 1983 and 1984 seasons revealed that canopy development in the three phenotypes was similar until late in the season and proceeded as follows:

i) After emergence plants fell over when only a few centimetres tall. Collapse at this stage is not important as the plants recover, and hence is not to be confused with the damaging collapse of the mature canopy. Plate V shows a semileafless crop in mid-season. The lowest part of the main stem of all plants can clearly be seen to be laying flat on the ground. No damage was suffered at this stage as the stems were very flexible and their tissues were capable of withstanding such deformation. Clearly the ability to fall over without incurring damage helps plants in the wild meet stiffer plants to climb up.

ii) An erect canopy structure only started to develop when plants were close enough, and petioles long enough, to meet other plants and for strong connections to form through the tendrils. These connections give the canopy a framed structure. Lateral displacement of plants by the wind or by vigorous shaking was very limited due to the strength of this framework.

iii) In the middle of the season all four varieties grew well with canopies reaching a height of about 70 to 75 cms at the time when pods appeared (plate V). As the pods started to fill out the plants began drying off from the

Plate V The semileafless variety Filigreen standing in mid-season. The basal section of the stem of each plant is lying flat on the ground (see text). The extensive network between plants formed by the tendrils is also visible.

base upwards, resulting in the weakening of structural elements in the lower levels of the canopy (see below). As stems and petioles aged they became stiffer, and could not be bent to the same degree as earlier in the season without suffering serious damage.

iv) Lodging was initialised by failure in the lowest levels of the canopy. At higher levels canopy structure was little different to that observed earlier in the season; the rigidity of the framework formed by the plants seemed to be little changed. It thus seems likely that the principal mechanism for lodging in dried pea crops is through buckling of stems in the lowest levels of the canopy. The action of wind certainly contributes to canopy collapse (even very slight lateral displacement will encourage buckling) though comparison of the momentum absorption characteristics of crops (chapters 3 and 4) of the different phenotypes is necessary to assess the role of the wind more accurately.

v) Once the stems and petioles lower down had failed, the upper canopy gradually followed, and eventually crops became fully compacted after a period of about two weeks (see plate VI). Even when the canopy was fully flattened, tendrils held the drying plants together (this being most clearly evident at harvest), demonstrating that the connections between plants did not fail at any time.

Plate VI Crops of the semileafless variety Filigreen (in the foreground) and the leafless variety Filby (in the background) shortly before harvest. The semileafless canopy had completely collapsed whilst the leafless canopy was still standing. Note that the stems of the lodged crop are all lying in the same direction, indicating the degree of mutual support found in pea canopies.

The vertical distribution of fresh mass at lodging (figure 2.8) in the field plots shows that all four varieties were distinctly top heavy. The distribution expressed as the percentage of the total fresh mass of each variety in each stratum (figure 2.9) shows that a similar pattern was present in all four varieties, with more than 50% of canopy mass concentrated in the strata above 45 cms. This was due mostly to the fact that pods were produced only in the upper canopy (figure 2.10) with all, except a few on the smallest plants, found above 30 cms.

The concentration of leaves into the lowest layer of the canopy (see figure 2.11) was due to short internode lengths between the leaves produced shortly after germination and the limited buckling of stems under the increasing weight as the plants grew. Similar numbers of leaves were found in the mid-canopy layers for the four varieties. Any increase in numbers of leaves at the top of the canopy was due to incomplete internode extension in this region by the time lodging occurred. The high percentage of leaf (by numbers of leaves) in the lowest level only contributed about 10% to the total leaf area (figures 2.12 and 2.13), with most leaf area present above 30 cms (further contributing to the top heavy distribution of fresh mass found above). Most leaves in the lowest level were smaller than those higher up (being the oldest) and many, due to redistribution of assimilate as they became shaded were shrivelled and dead. Concentration of

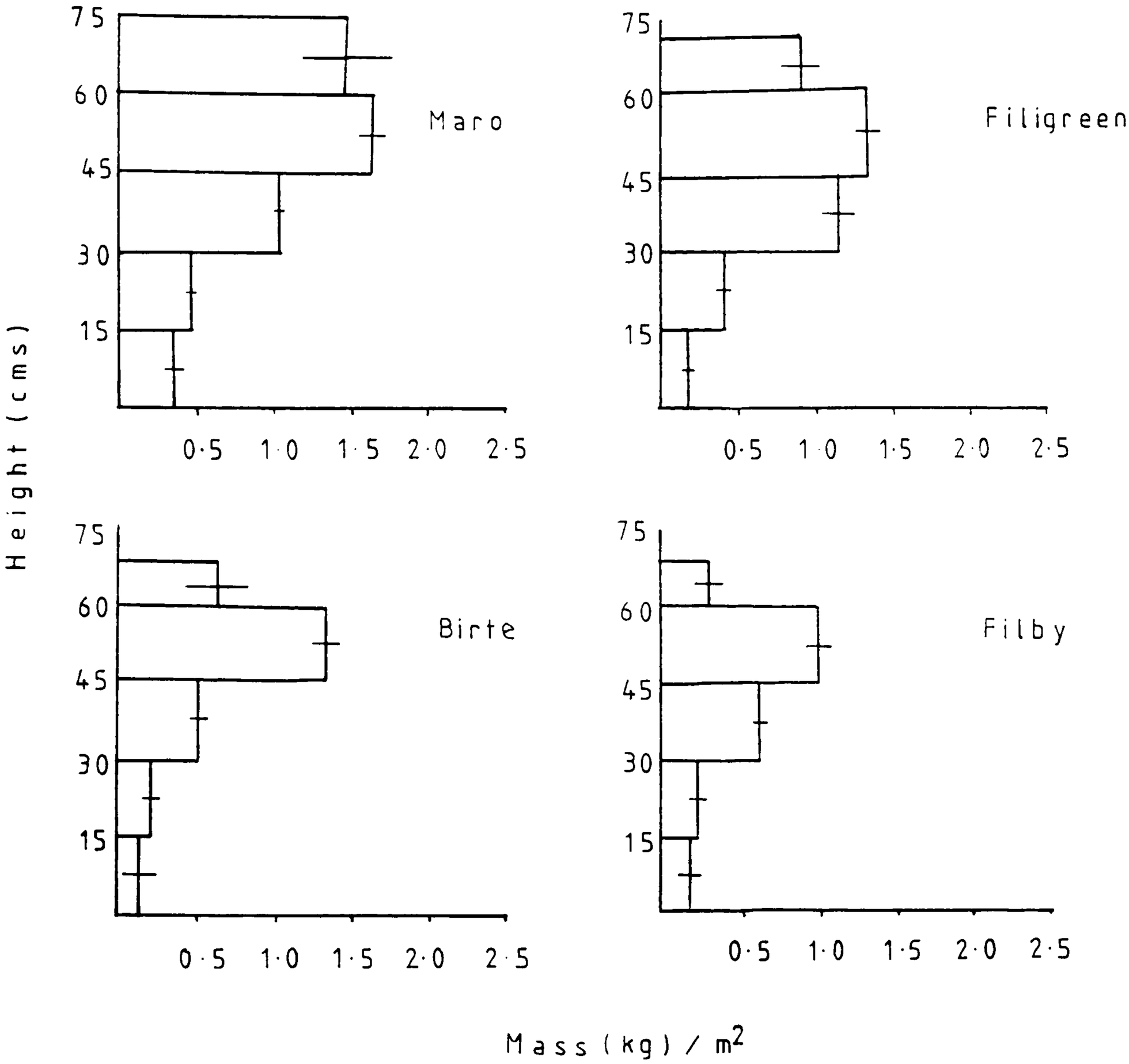


Figure 2.8 Vertical distributions of fresh mass per unit ground area for Maro, Birte (both conventional), Filigreen (semileafless) and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

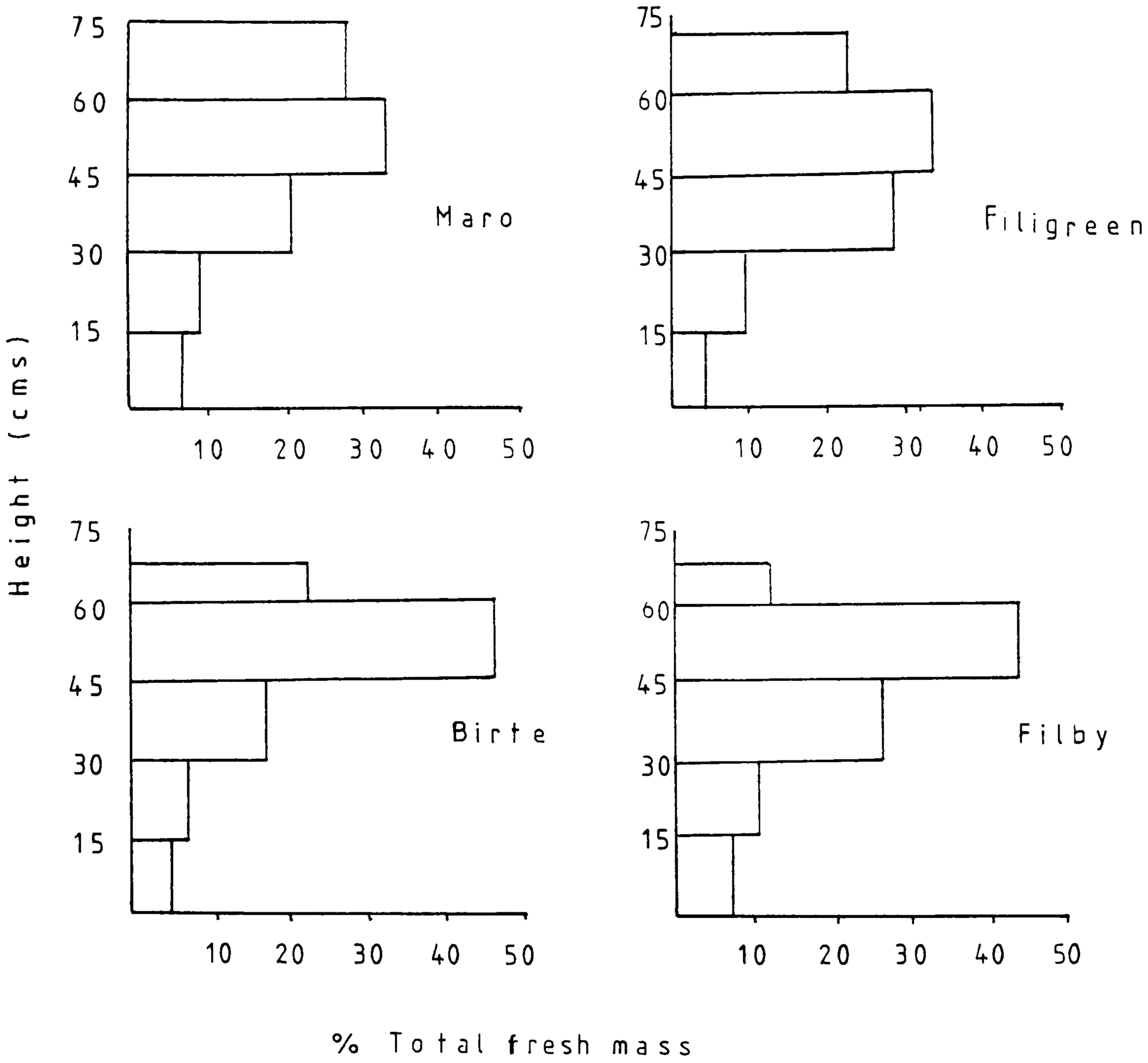


Figure 2.9 Vertical distribution of fresh mass (expressed as a percentage of the total for each variety) for Maro, Birte (both conventional), Filigreen (semileafless) and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

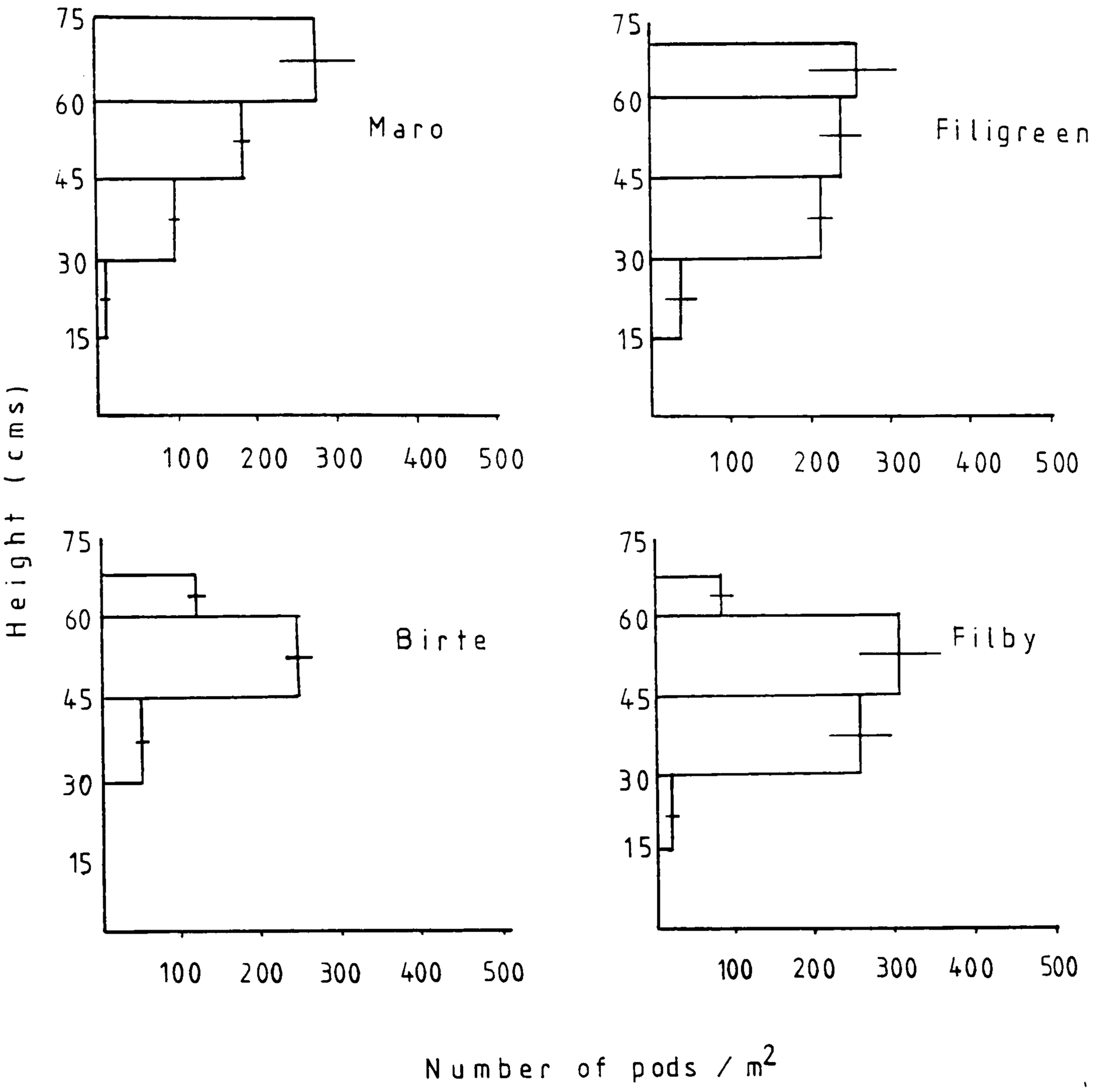


Figure 2.10 Vertical distribution of the number of pods per unit ground area for the varieties Maro, Birte (both conventional), Filigreen (semileafless) and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

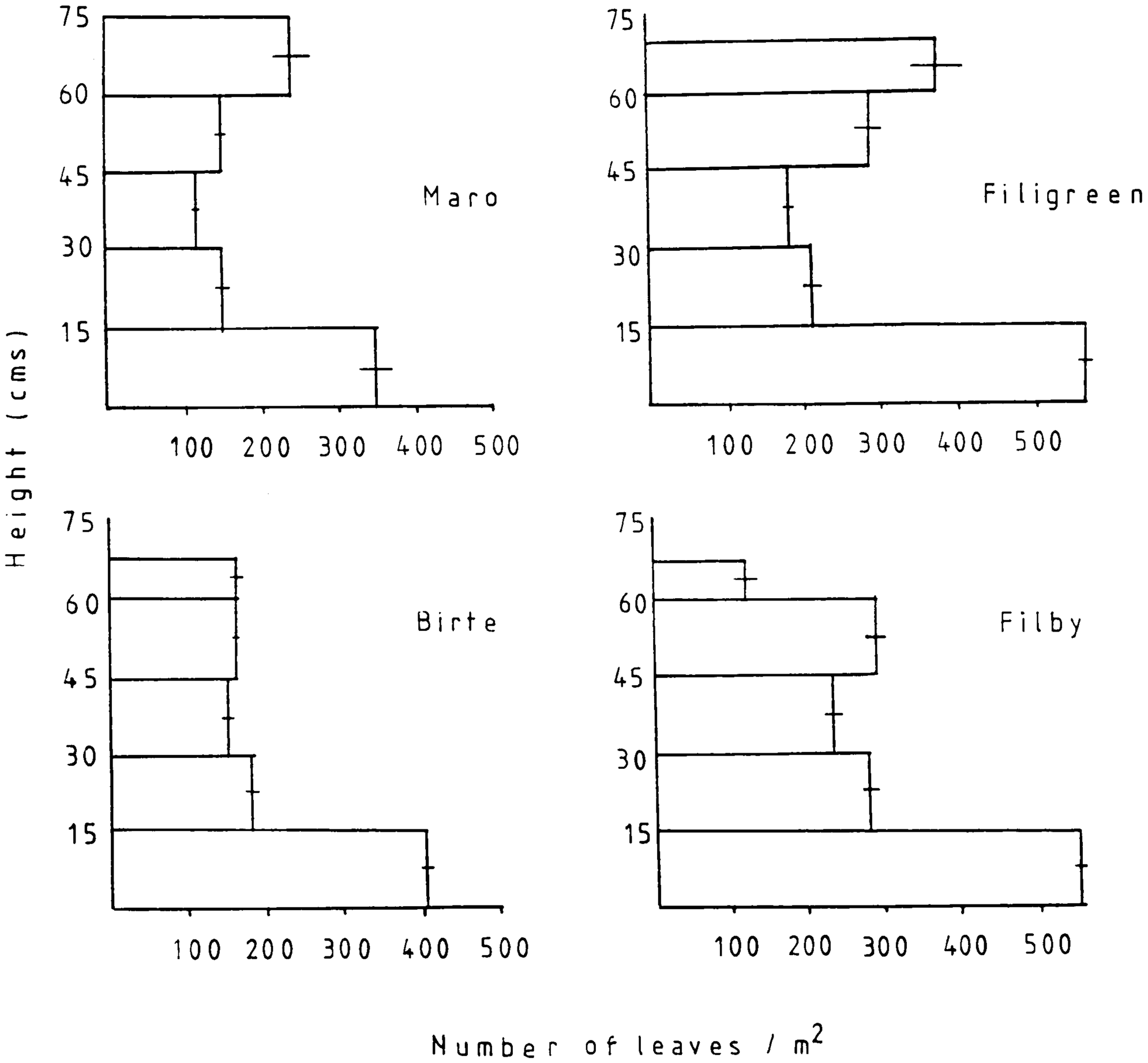


Figure 2.11 Vertical distribution of the number of leaves per unit ground area for the varieties Maro, Birte (both conventional), Filigreen (semileafless) and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

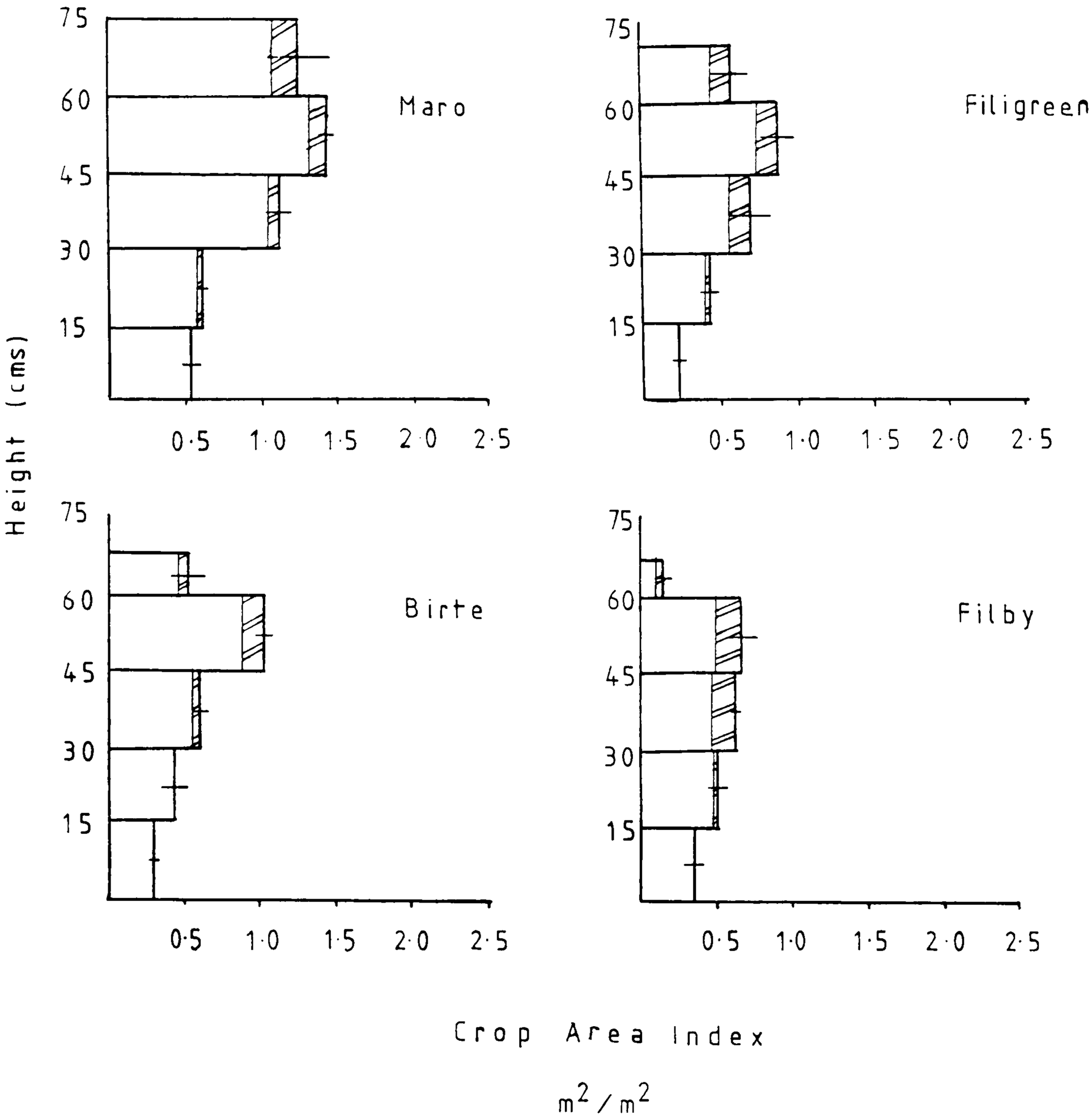


Figure 2.12 Vertical distribution of crop area (the combined area of leaves, pods and stem) per unit ground area for the varieties Maro, Birte (both conventional), Filigreen (semileafless), and Filby (leafless) in the supported areas of the field plots at lodging. Unshaded bars give the area of leaves and stems in each stratum whilst shaded bars show the area of pods. Area data were used in the calculation of shelter factors for momentum transfer in chapter 4, below. Standard error bars are shown.

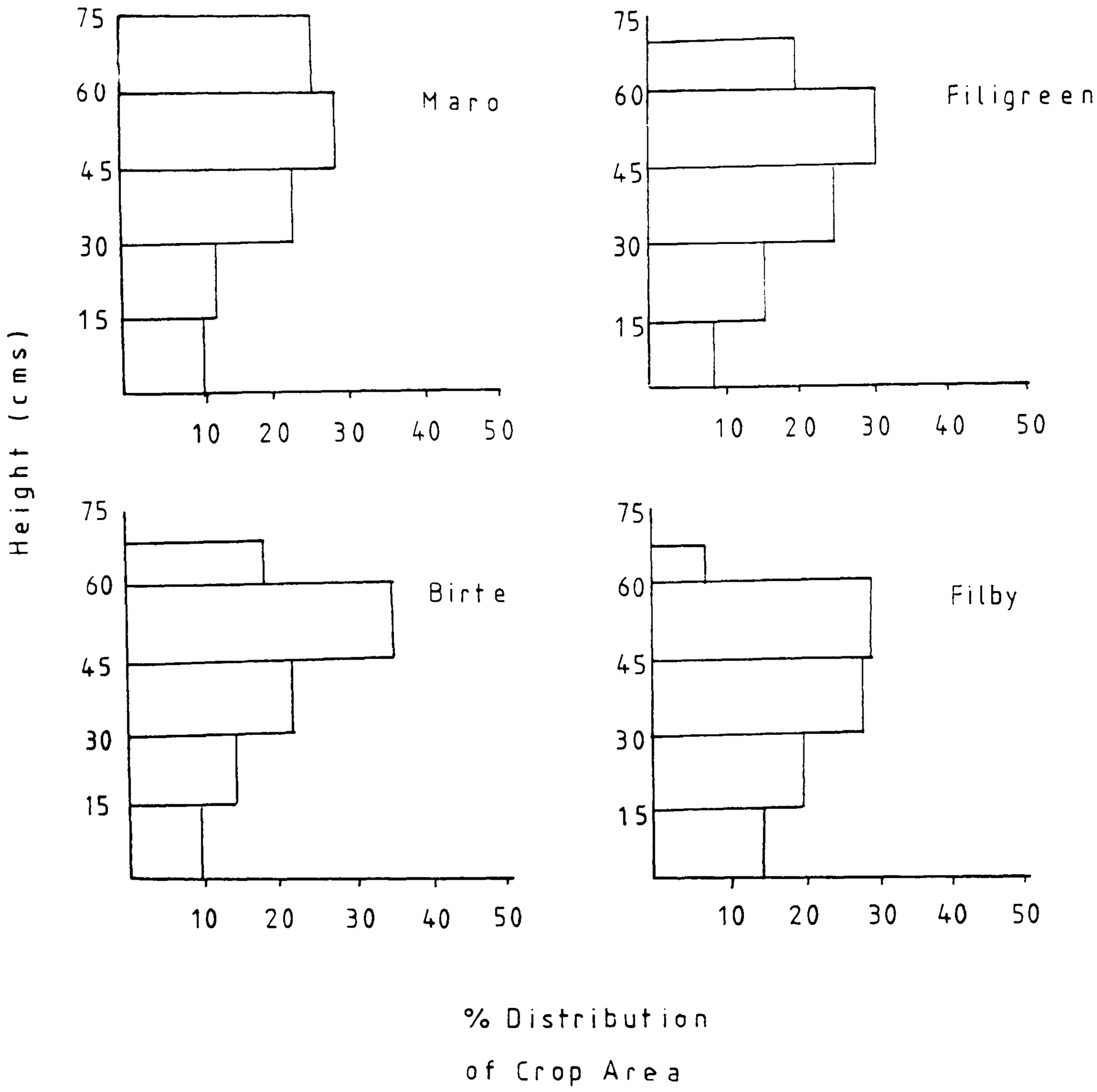


Figure 2.13 Vertical distribution of crop area (expressed as a percentage of the total for each variety) for the varieties Maro, Birte (both conventional), Filigreen (semileafless), and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

leaf area into the upper canopy was not, perhaps, so marked for the leafless Filby. Total crop area indices for each variety at lodging are given in table 2.3:

Table 2.3 Mean crop area indices (calculated from the combined area of leaves, stems, and pods) at lodging for the four varieties in the field plots. Values followed by the same letter are not significantly different.

Maro (conventional)	5.05 m^2/m^2	a
Birte (conventional)	2.93 m^2/m^2	b
Filigreen (semileafless)	2.90 m^2/m^2	b
Filby (leafless)	2.11 m^2/m^2	c

The lower sowing density of the conventionals made no significant difference to the number of connections (via tendrils) between plants per plant (figure 2.14). In all four varieties approximately two connections per 15 cm stratum were made, despite any variation in numbers of leaves with height. As would be expected this was largely a function of the number of leaves in each stratum, apart from in the lowest layer where many leaves were too small to reach other plants. A difference between varieties was found, however, in the total number of plants each plant was connected to (table 2.4). The differences can be explained through observations on the manner in which these varieties grow. Filigreen stems were quite notably

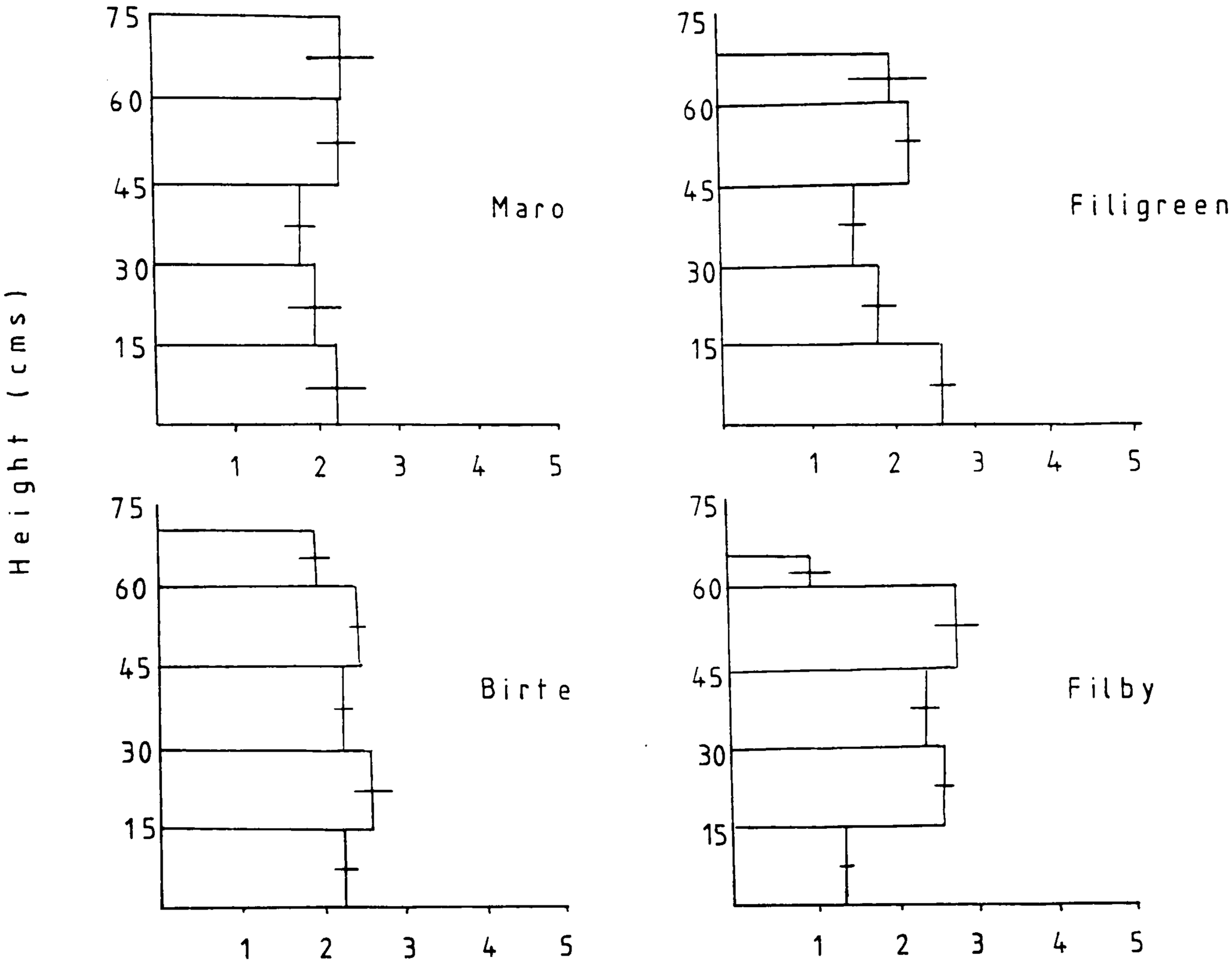


Figure 2.14 Vertical distribution of the number of connections between plants per plant for the varieties Maro, Birte (both conventional), Filigreen (semileafless) and Filby (leafless) in the supported areas of the field plots at lodging. Standard error bars are shown.

erect, hence the number of plants that any individual could be directly connected to was limited to those plants immediately surrounding it. Birte, however, did not grow so straight and hence was free to form connections with more plants.

Table 2.4 Mean numbers of individuals each plant is connected to in canopies of Maro, Birte, Filigreen and Filby. Values followed by the same letter are not significantly different.

Maro (conventional)	6.4	a
Birte (conventional)	7.9	b
Filigreen (semileafless)	5.5	c
Filby (leafless)	6.3	a

NIAB trial plots

Measurements of canopy height in the NIAB trial plots are shown in figure 2.15. Most of the varieties studied had very poor standing ability, almost all lodged completely. The most stable varieties were Consort (semileafless), Progreta (tare-leaved rogue), and Sentinel (semileafless).

Microplots

Canopy structure was assessed for Sentinel and Progreta (due to their performace in the NIAB trial plots), and the cultivar BS679 which stood well in the microplots.

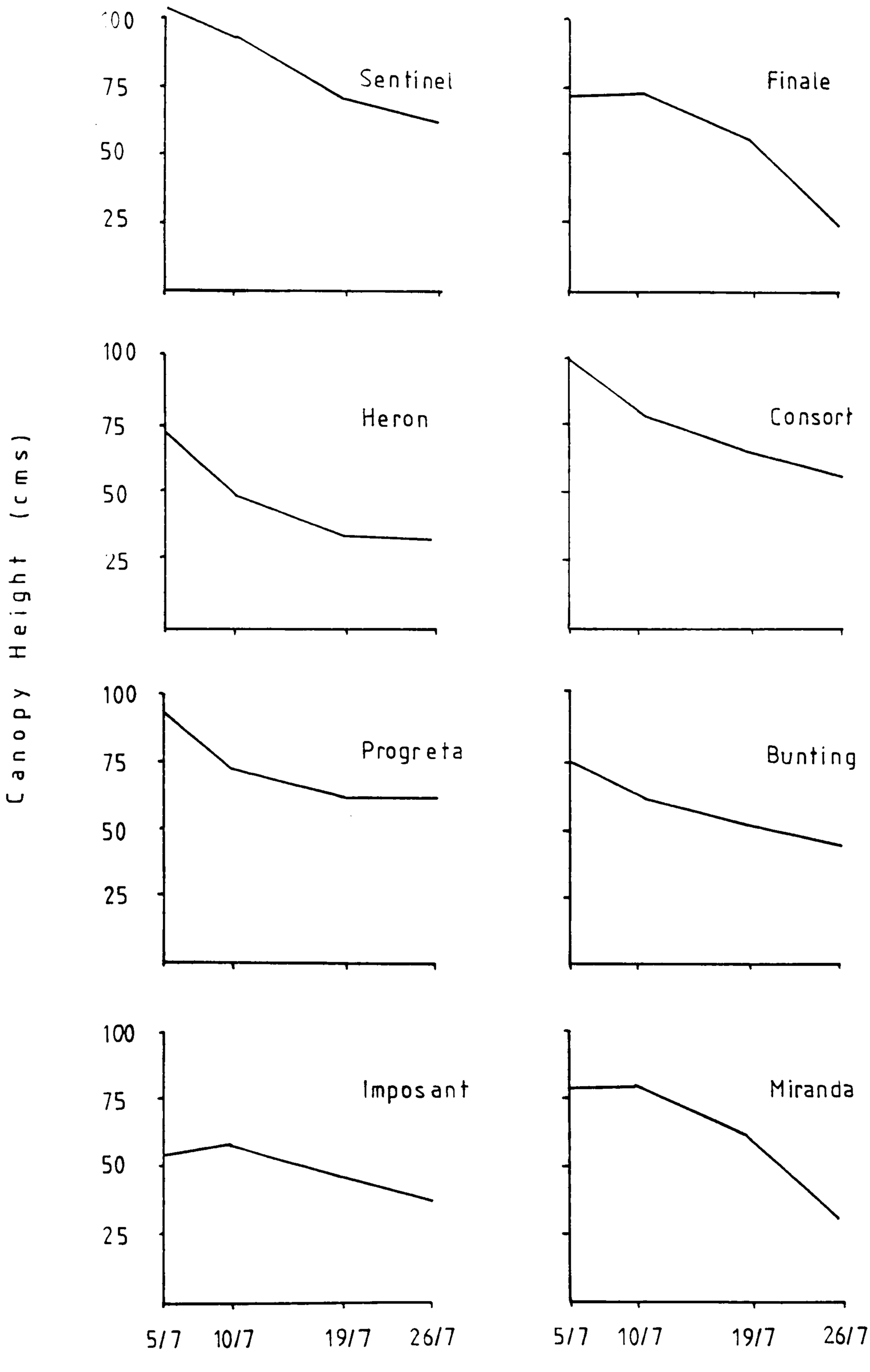


Figure 2.15 Canopy height in the NIAB trial plots from July 5th 1984 until harvest.

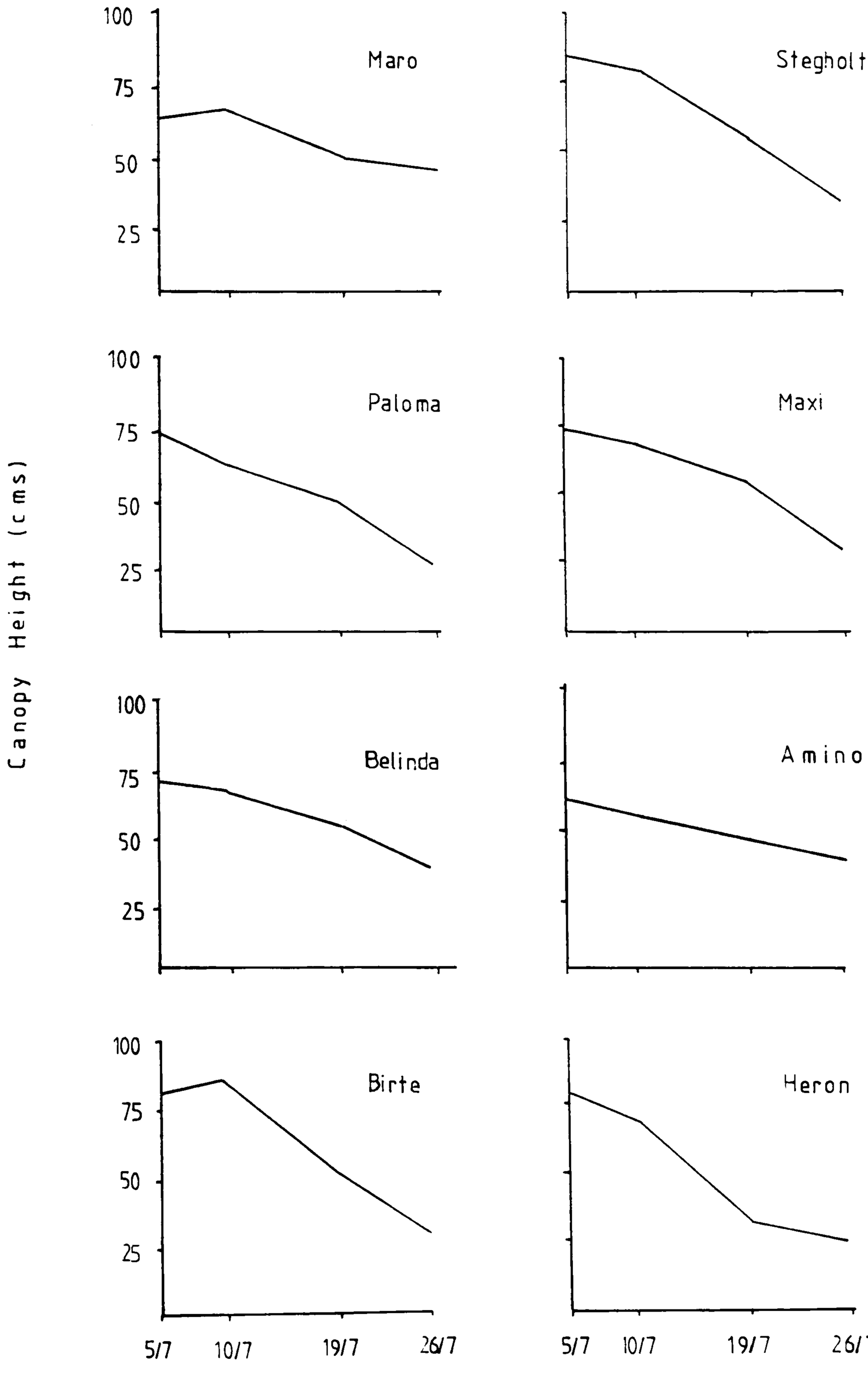


Figure 2.15 (continued)

Weakness of the canopy in many varieties as the crop dried out was reflected by the sagging of plants even in the microplots, despite the extra support given (see table 2.5), with all varieties going down to less than 80% of their earlier height and most to less than 70%. To some extent this weakness can probably be attributed to the additional support, as standing may be achieved with less resources allocated to stem strength than normal. In the microplot environment, standing ability of the variety Consort was not good in comparison to other varieties, and hence, despite its good performance in the NIAB trial plots, was not studied further. It has been reported elsewhere (Wilkinson, 1986) that standing ability of this variety is somewhat variable.

Fresh mass was most concentrated in the upper canopy (like the distributions seen in the field crops) for Sentinel and Progreta (figures 2.16 and 2.17). A slightly different distribution was found with BS679: mass was spread more evenly throughout the canopy though it was still top heavy. Like the plants grown in the field plots the distribution of fresh mass with height was influenced mainly by the distribution of pods within the canopy (figure 2.18). Distributions of leaves (figure 2.19) were also similar to the distributions found for the field crops. The total fresh masses of plants from the microplots were less than those measured for the varieties from the field plots. It is possible that plants in the

Table 2.5 Height of canopies in the microplots before harvest expressed as a percentage of the maximum height reached by each variety.

Variety	Height at harvest as a % of maximum canopy height
BS4	76.8
BS151	64.9
Maro	58.4
BS51	71.0
BS679	79.0
Stegholt	79.3*
Progreta	67.3
Novella	44.2
Palla	64.8
Consort	66.9
Birte	38.2
Folio	63.2
Sentinel	78.9

* Values are all means of three plots except for the variety Stegholt for which only one plot was available.

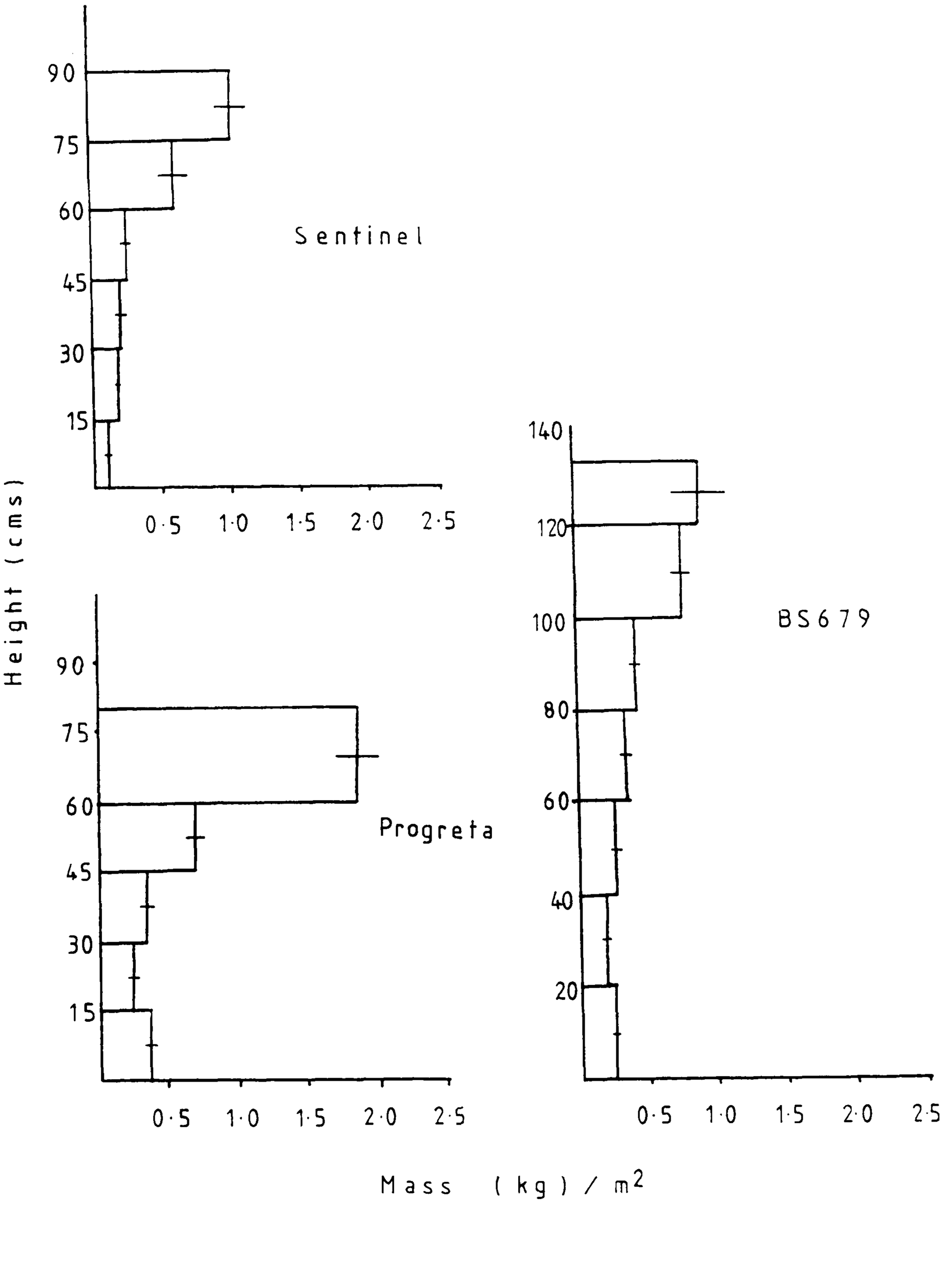


Figure 2.16 Vertical distribution of fresh mass per unit ground area for the varieties Sentinel (stiff stemmed), Progreta (rogue), and BS679 (stiff stemmed) in the microplots at lodging. Standard error bars are shown.

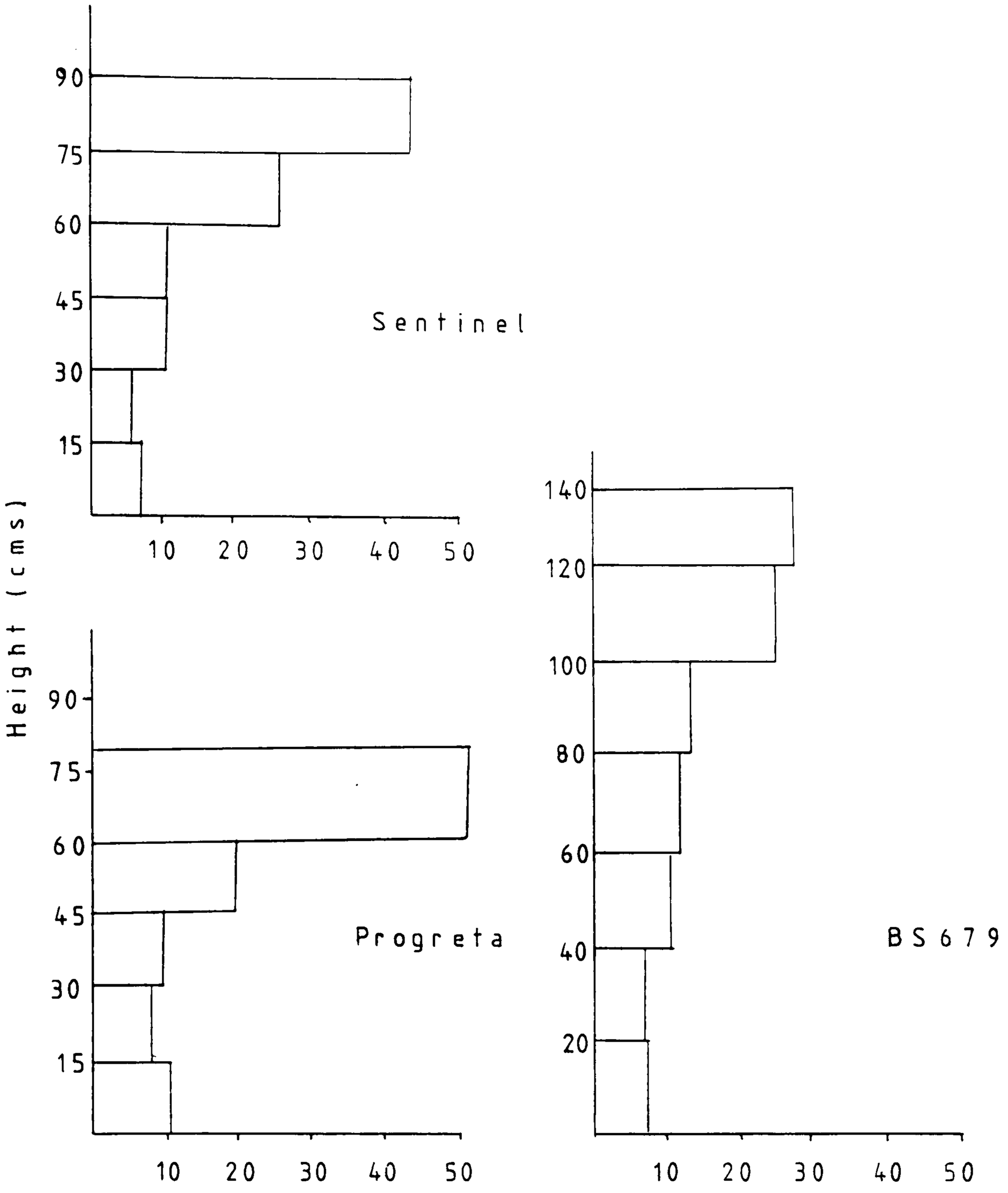


Figure 2.17 Vertical distribution of fresh mass (expressed as a percentage of the total for each variety) for the varieties Sentinel (stiff stemmed), Progreta (rogue), and BS679 (stiff stemmed) in the microplots at lodging. Standard error bars are shown.

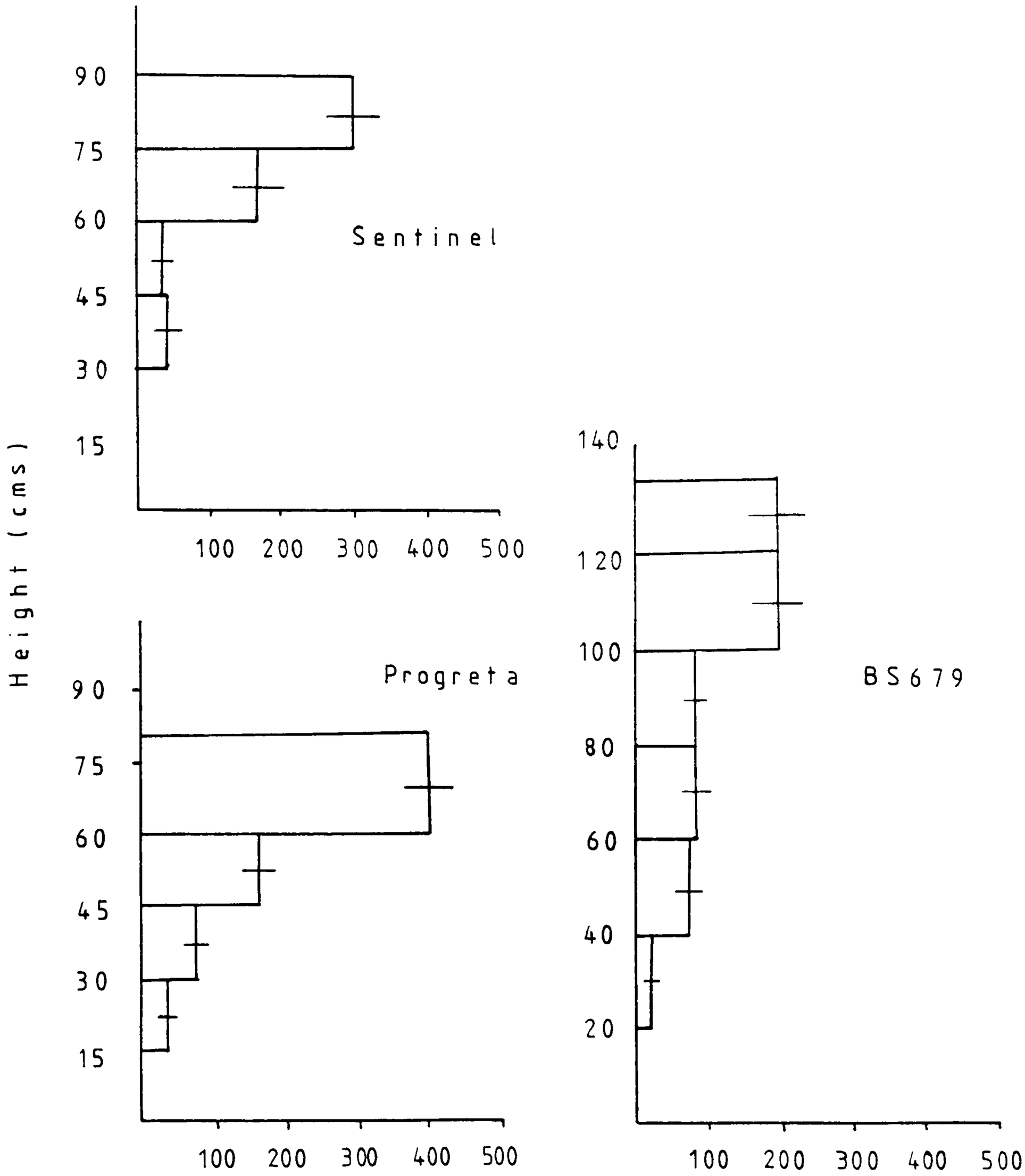


Figure 2.18 Vertical distribution of the number of pods per unit ground area for the varieties Sentinel (stiff stemmed), Progreta (rogue), and BS679 (stiff stemmed) in the microplots at lodging. Standard error bars are shown.

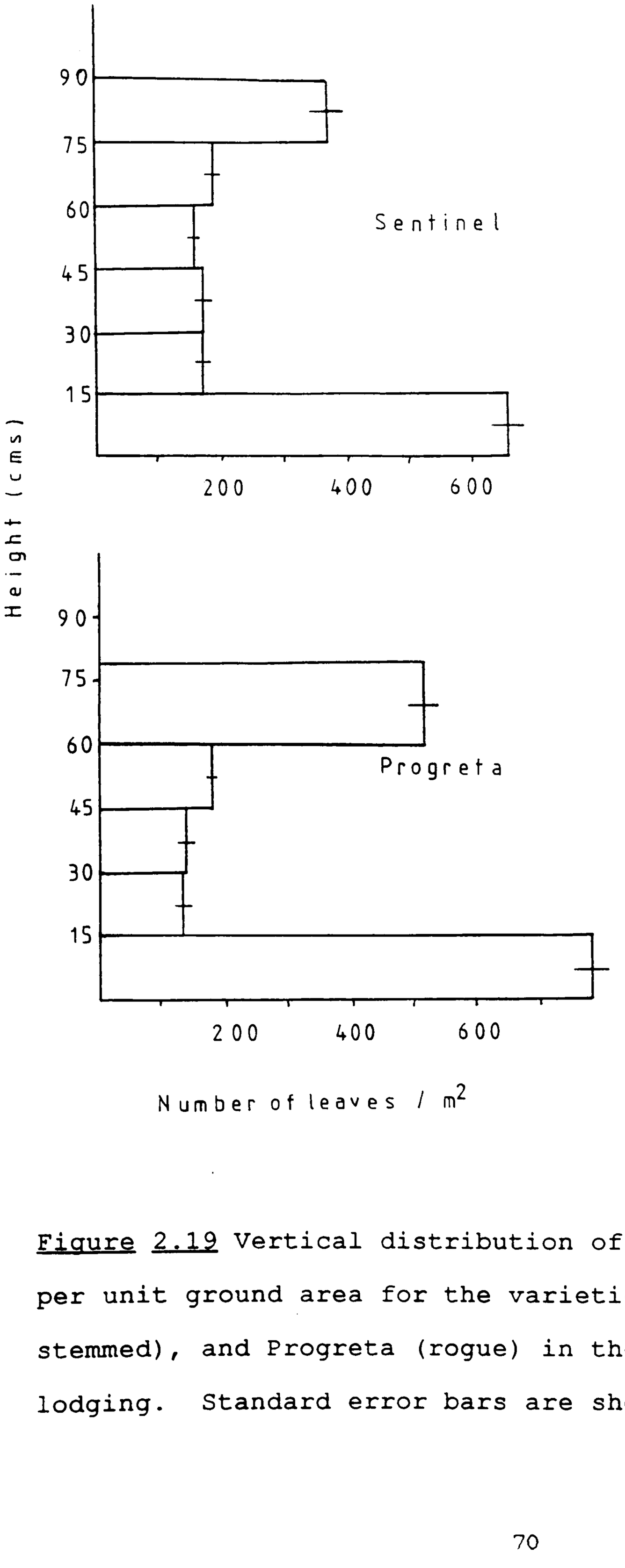


Figure 2.19 Vertical distribution of the number of leaves per unit ground area for the varieties Sentinel (stiff stemmed), and Progreta (rogue) in the microplots at lodging. Standard error bars are shown.

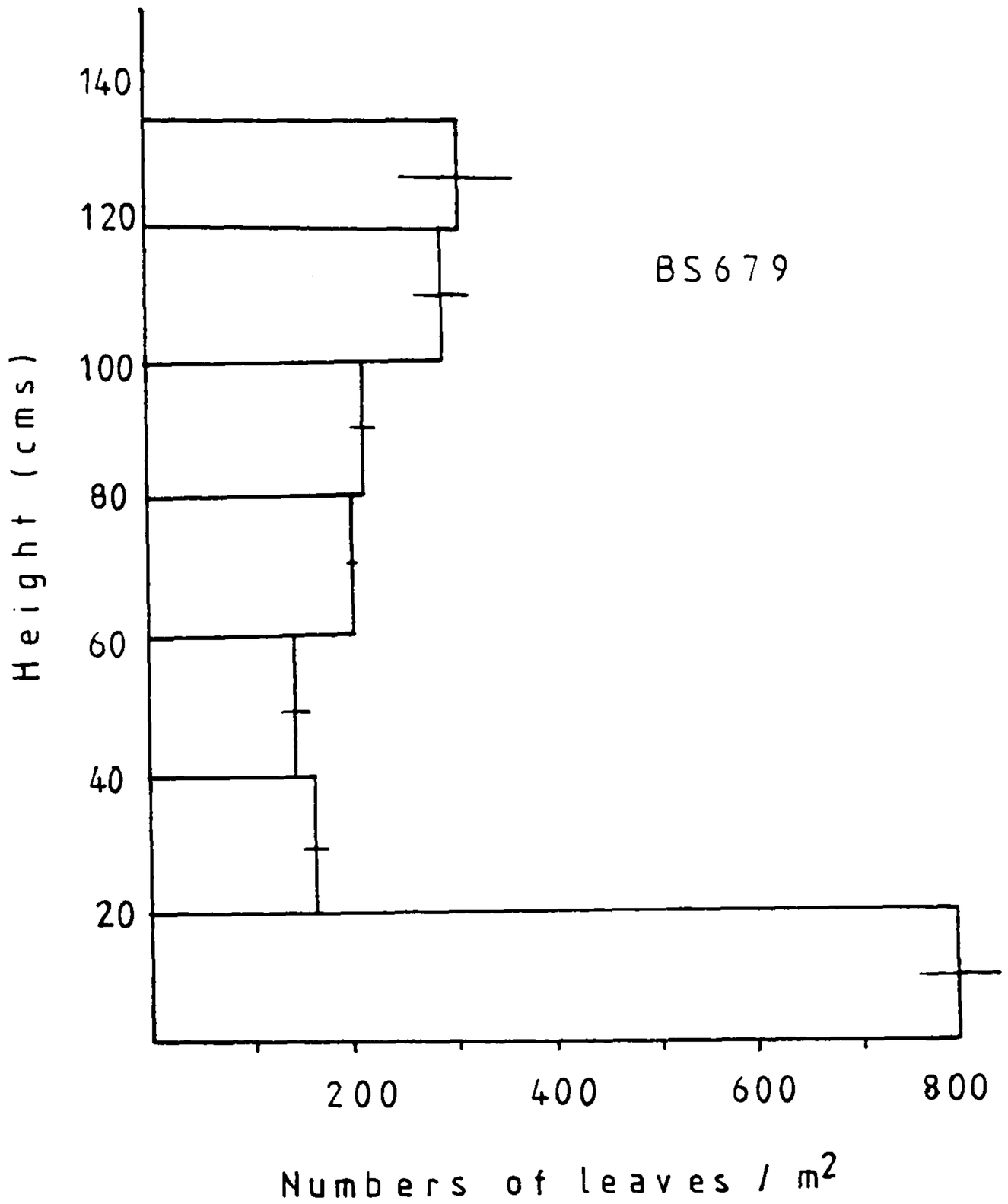


Figure 2.19 (continued) Vertical distribution of the number of leaves per unit ground area for the stiff stemmed cultivar BS679 from the microplots at lodging. Standard error bars are shown.

microplots were harvested later than they would have been had they been grown in the open, as the exact time of lodging was uncertain due to the extra support provided.

Water carrying capacity of leaves

Bunches of tendrils were found to be much more effective at trapping water droplets than leaves. Droplets on leaf surfaces, held together by their surface tension, tended to roll around on the waxy leaf surfaces and form large droplets that rolled off if disturbed. On tendrils, however, many small droplets formed that were unable to coalesce into larger droplets and which would not roll off as easily as they might on a flat leaf surface. The amount of water carried by pods was found to be minimal. Due to the vertical manner in which pods are held water was found to drip away very quickly. Mean values of the ratio of water carried to leaf area for conventional, semileafless, and leafless phenotypes are shown in table 2.6. Using these ratios and the values for leaf and stem area index found above for the field crops (from figure 2.12) the amount of water capable of being carried by the canopies per unit ground area is shown in table 2.7.

Mechanical attributes of stems and petioles

Values of (Y), (I_g), and (M_{max}) for the near isogenic cultivars, and the varieties Maro, Filigreen, Filby, Sentinel and Progreta are shown in figures 2.20 to 2.28. It should be noted that the scales of these graphs are not

Table 2.6 Ratio of water carried (kg) to leaf area (m^2) for near-isogenic conventional, semileafless and leafless phenotypes, with 95% confidence limits.

Conventional	0.056 ± 0.011 kg/m^2
Semileafless	0.102 ± 0.026 kg/m^2
Leafless	0.320 ± 0.083 kg/m^2

Table 2.7 Water carrying capacity per unit ground area at lodging for the field crops, calculated from table 2.6 and figure 2.12.

Maro (conventional)	0.253 ± 0.056 kg/m^2
Birte (conventional)	0.144 ± 0.032 kg/m^2
Filigreen (semileafless)	0.206 ± 0.075 kg/m^2
Filby (leafless)	0.475 ± 0.175 kg/m^2

consistent throughout due to the large differences between stems and petioles and to the size of the differences between varieties.

The values of (I_g) (figures 2.20, 2.21 and 2.22) increased towards the top of the plants for main stems and petioles in all of the varieties studied. In all cases (I_g) was greater for the main stem than the petioles at any particular height. However, the increase in (I_g) with height resulted in values for petioles near the top of the canopy exceeding those for main stems at the base in most varieties. At the stage when measurements were taken (just as the plants had started to dry out) it was clear that variation of (I_g) with height was exaggerated by the drying process, through shrinkage of the wall of tissue around the central cavity of the stems and petioles. (I_g) was generally higher for Sentinel and Progreta (the varieties seen to have good standing ability in the NIAB trial plots) than for the other varieties studied.

Values of Young's modulus are shown in figures 2.23, 2.24, and 2.25. There is no clear trend in the variation of (Y) with height for main stem samples between the varieties studied. For stems, values of (Y) varied between about 100 and 350 N mm^{-2}. In the conventional and semileafless near-isogenic cultivars (Y) increased between the lowest level and the next up, though declined thereafter. In the leafless cultivar, however, (Y) increased from the base

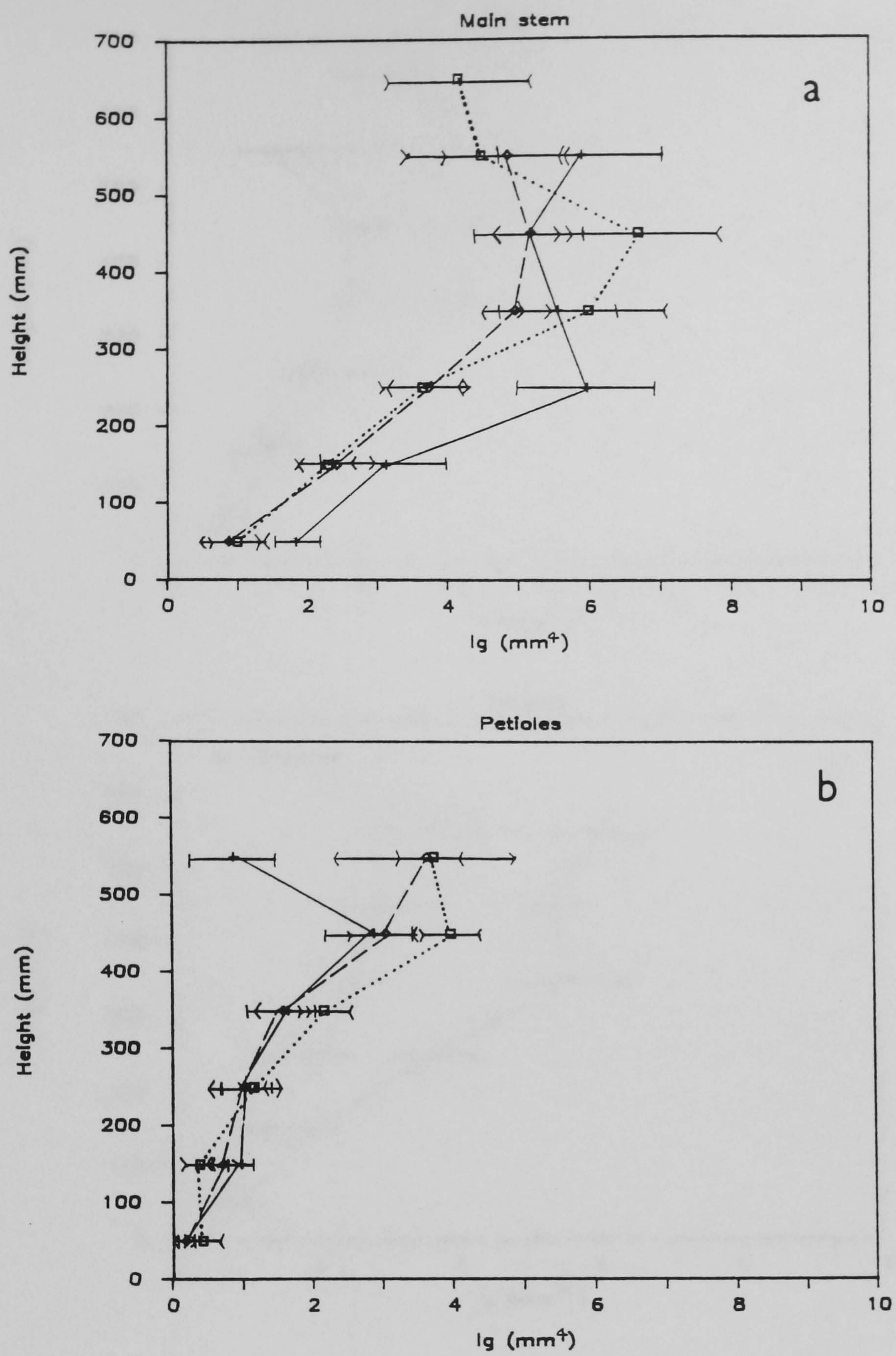


Figure 2.20 The second moment of area (I_g) for the near isogenic cultivars for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

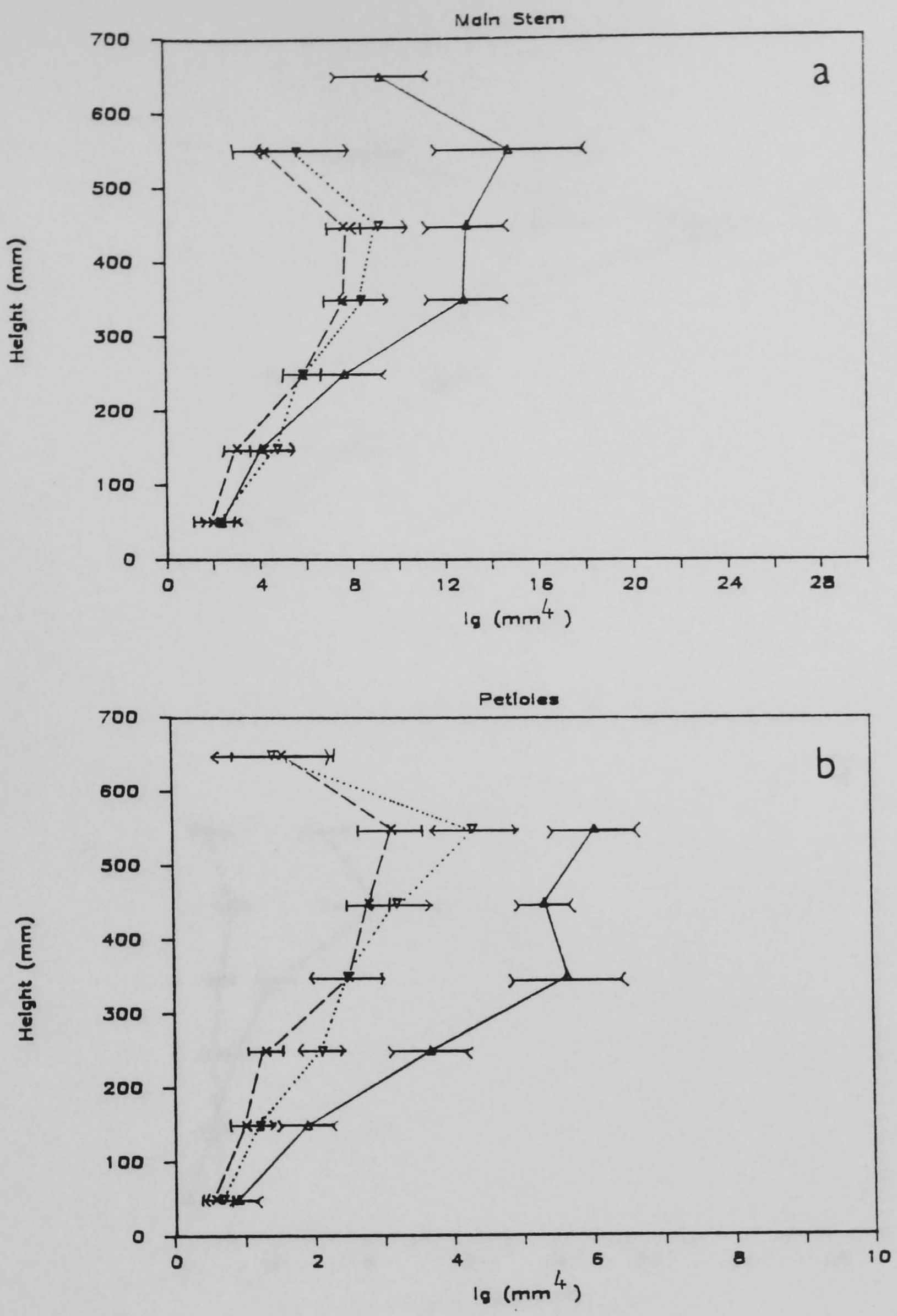


Figure 2.21 The second moment of area (I_g) for the varieties from the field plots for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown. Note the change in scale between (a) and (b).

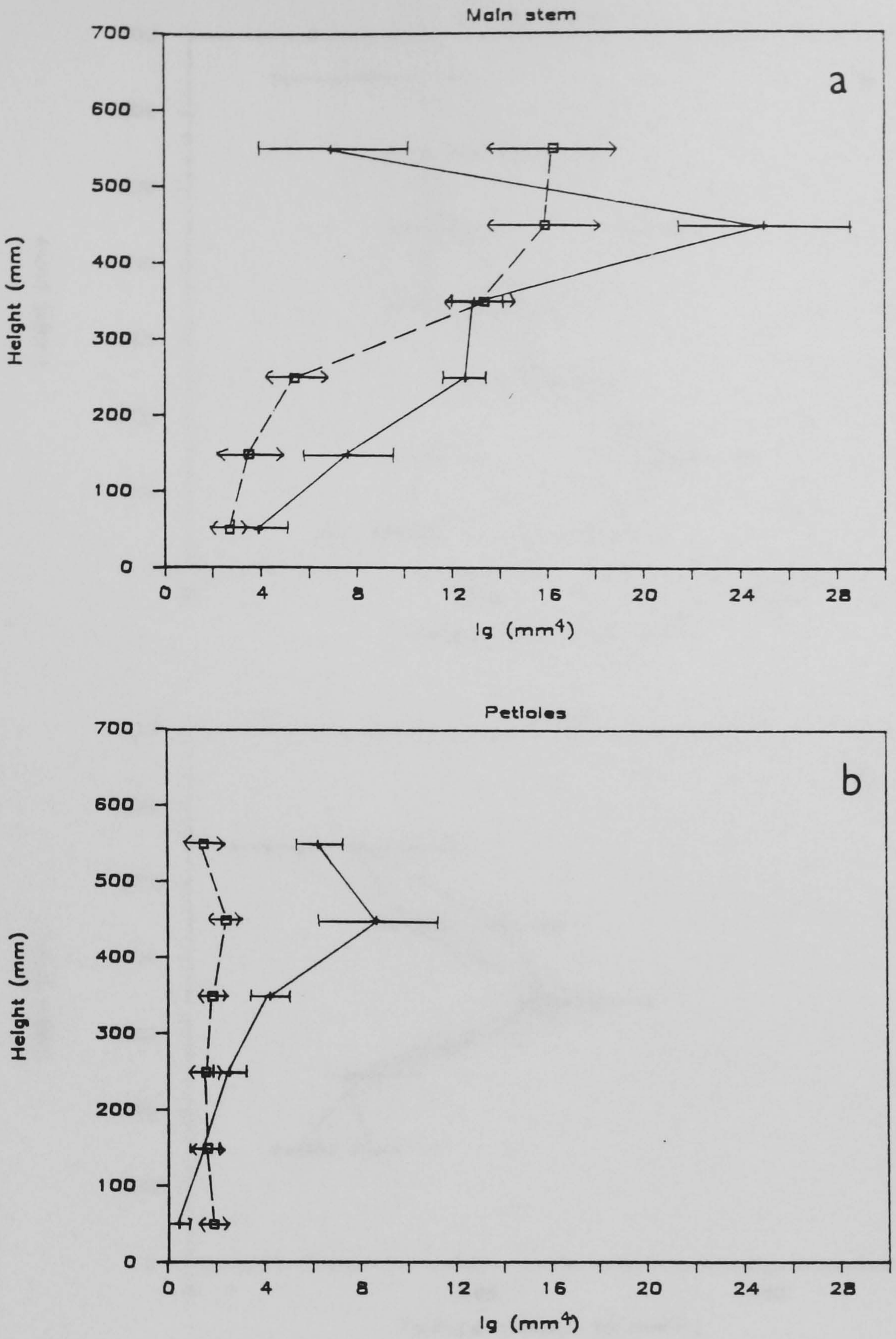


Figure 2.22 The second moment of area (I_g) for the varieties Progreta and Sentinel for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

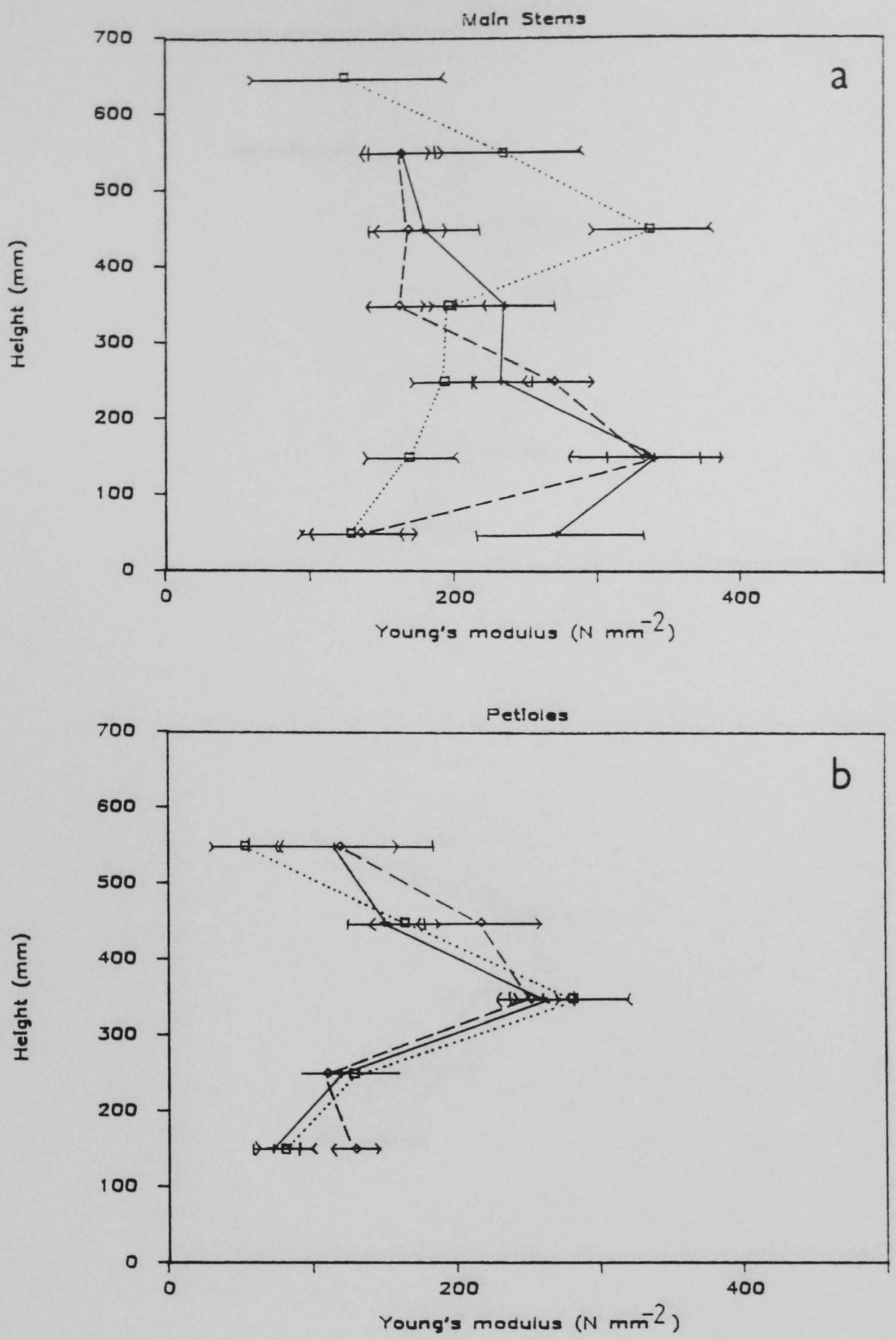


Figure 2.23 Young's modulus (Y) for the near isogenic cultivars for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

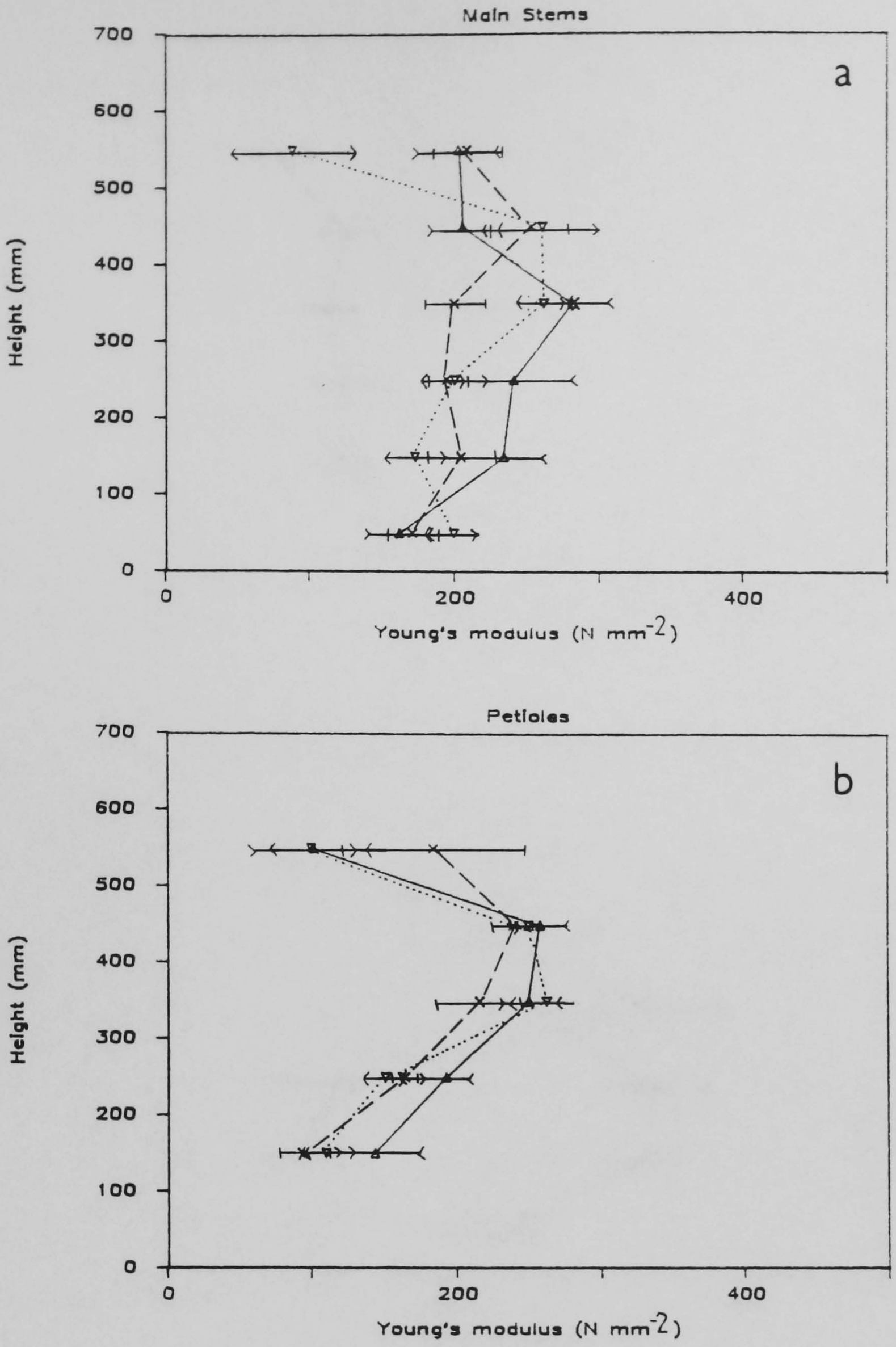


Figure 2.24 Young's modulus (Y) for the varieties from the field plots for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

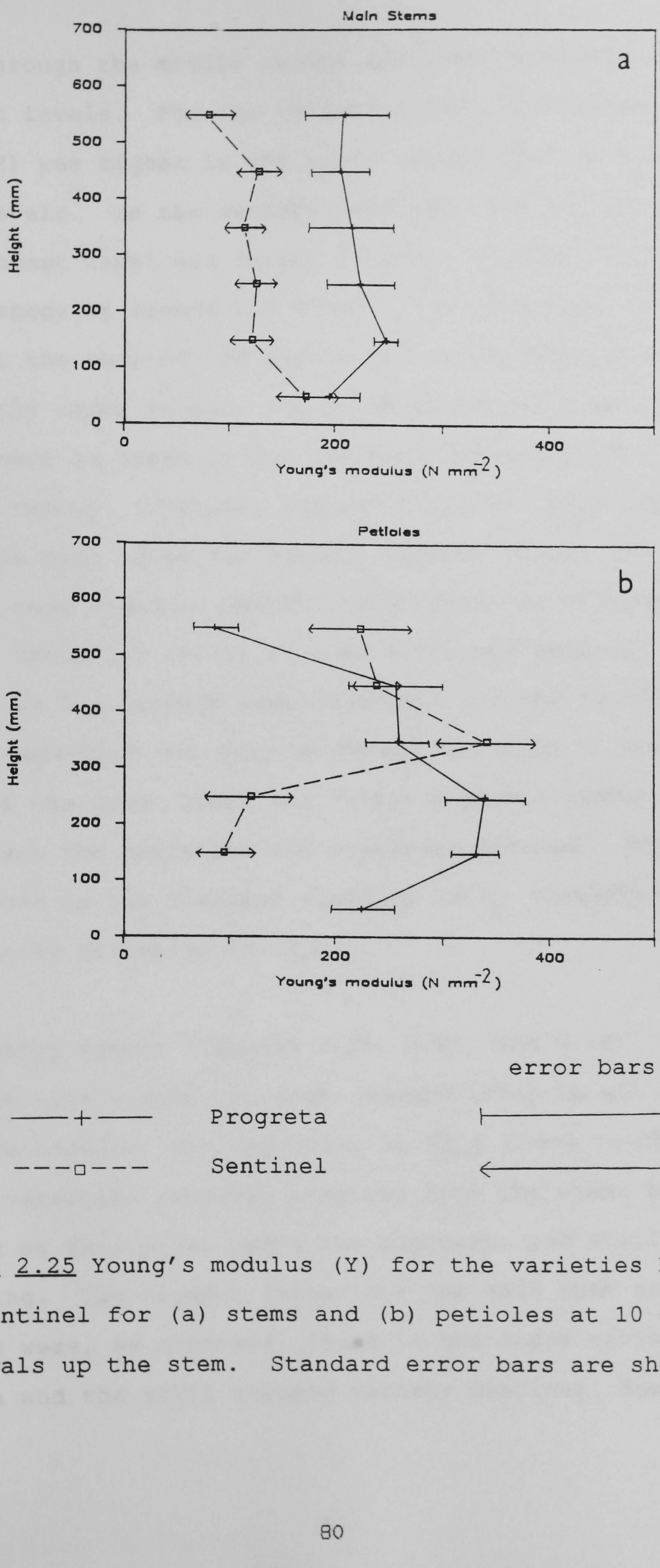


Figure 2.25 Young's modulus (Y) for the varieties Progreta and Sentinel for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

and up through the middle canopy and then decreased in the uppermost levels. For the varieties Maro, Filigreen and Filby, (Y) was higher in the upper canopy than in the lowest levels. In the variety Sentinel, (Y) was greatest in the lowest level and fairly constant through the rest of the canopy at around 110 N mm^{-2}. For Progreta, (Y) was lowest at the base of the plants and fairly constant through the upper layers, though at about 210 N mm^{-2} it was nearly twice as great as for the same layers in the Sentinel canopy. Overall, values of (Y) for petioles were comparable with those for stems. Highest values for the petioles were found in samples taken from the mid-canopy levels. Variation of (Y) in both stems and petioles appears, as has already been described for the variation in (I_g), dependent not only on height but also on the drying of the crop. There was little apparent variation in (Y) between the varieties and cultivars studied. Any differences in the flexural rigidity ($Y.I_g$) therefore seem to be due to variation in (I_g).

The breaking moment (figures 2.26, 2.27, and 2.28) increased with height for stems and petioles in all of the varieties studied. The reduction in (M_{max}) close to the top of most varieties probably resulted from the stems and petioles at this point being the youngest, and still developing. The highest values for the main stem and petioles were, as expected, found in the rogue variety Progreta and the stiff stemmed variety Sentinel. However,

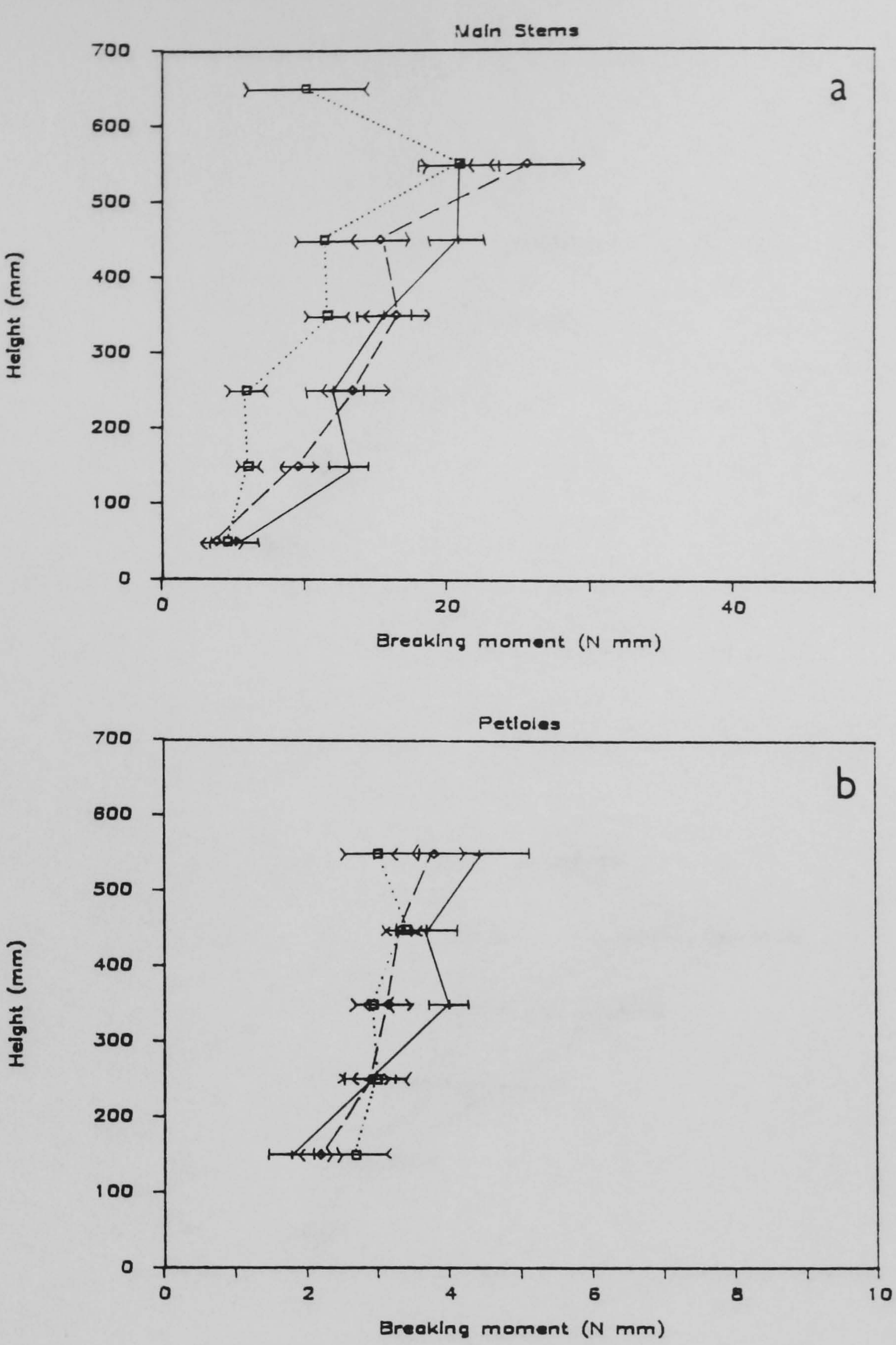


Figure 2.26 The breaking moment (M_{max}) for the near isogenic cultivars for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown. Note the change in scale between (a) and (b).

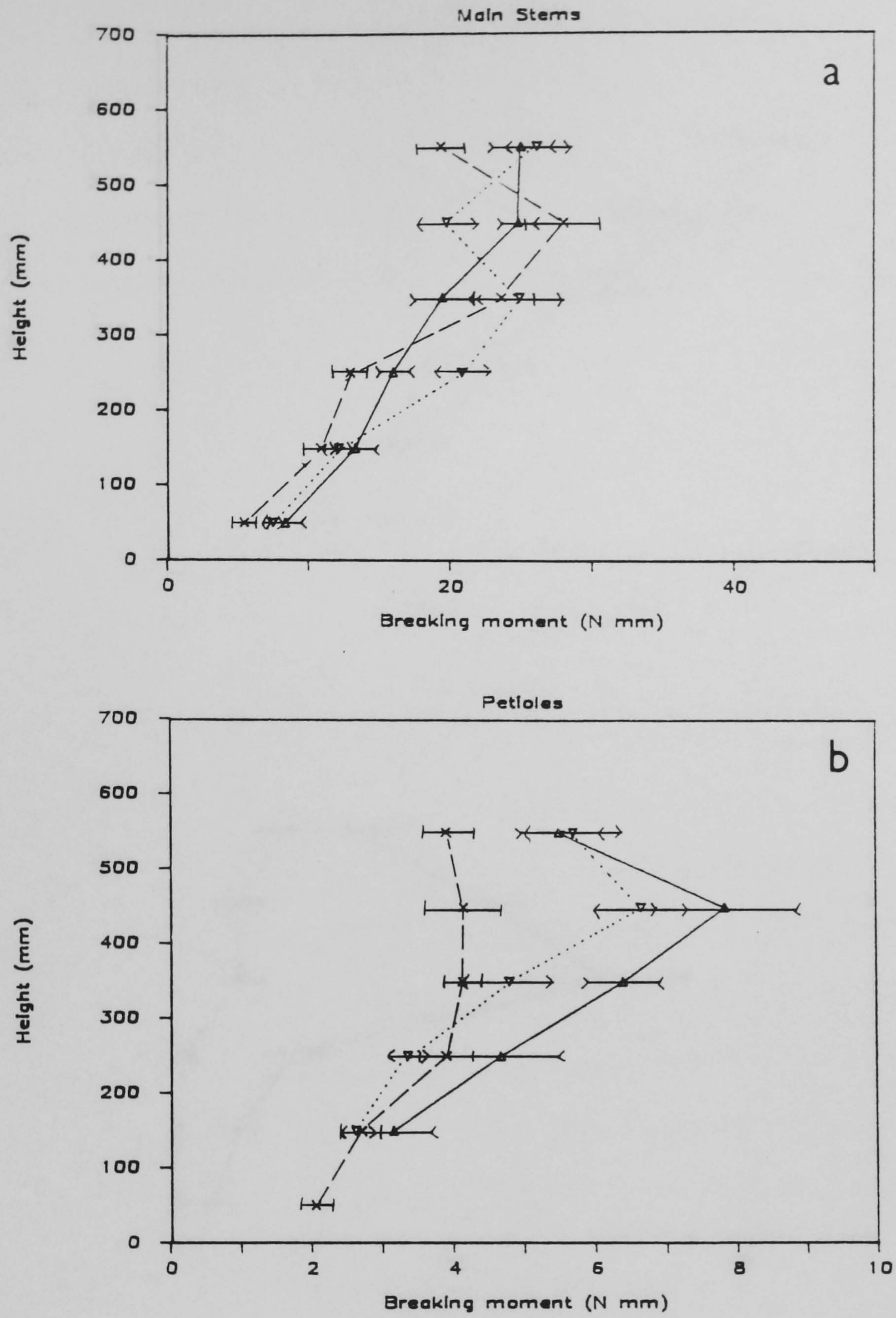


Figure 2.27 The breaking moment (M_{max}) for the varieties from the field plots for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown. Note the change in scale between (a) and (b).

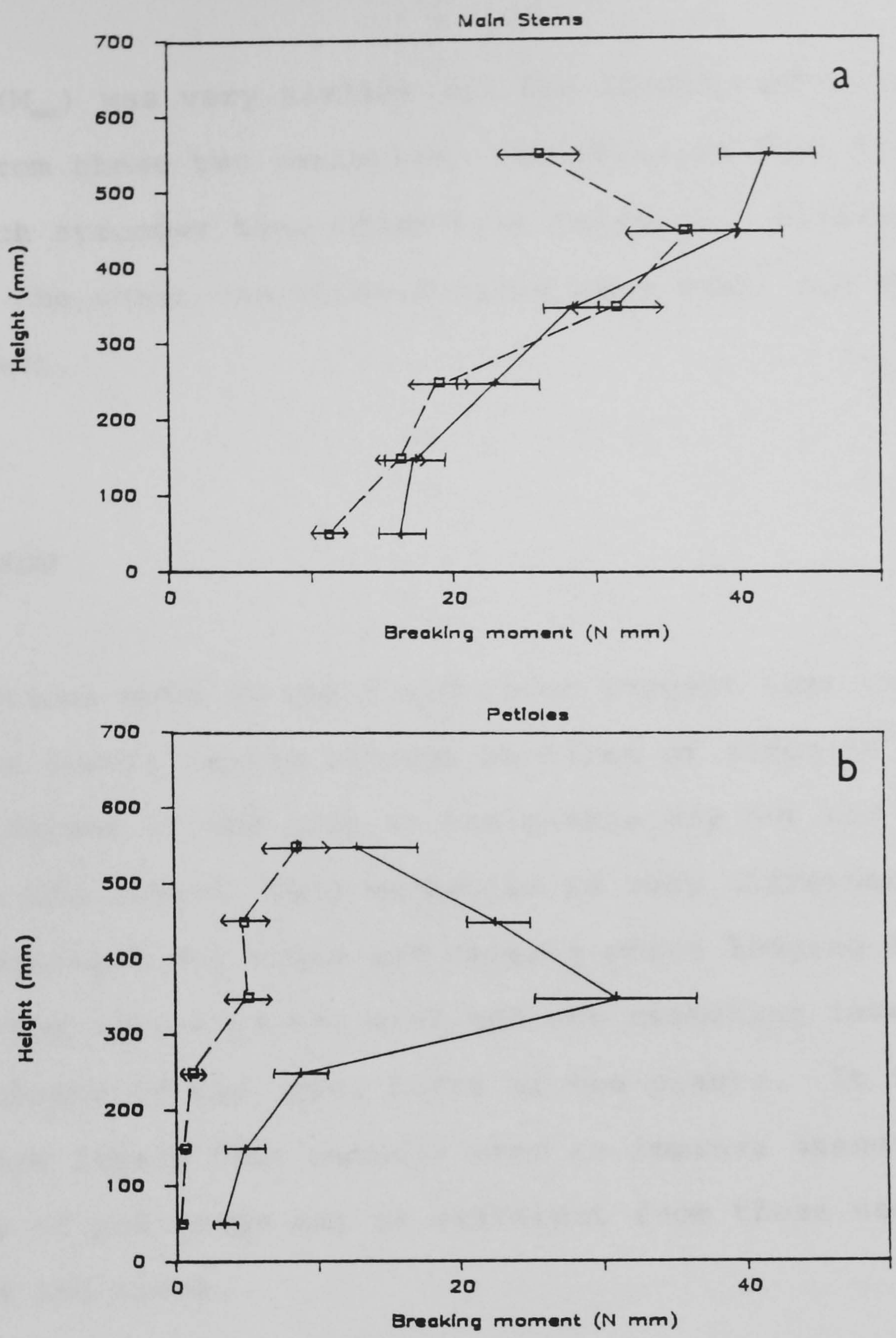


Figure 2.28 The breaking moment (M_{max}) for the varieties Progreta and Sentinel for (a) stems and (b) petioles at 10 cm intervals up the stem. Standard error bars are shown.

whilst (M_{max}) was very similar for the samples of main stem taken from these two varieties, the petioles from Progreta were much stronger than those from Sentinel. Differences between the other varieties studied were small and not consistent.

DISCUSSION

Observations made on the field crops suggest that canopy collapse occurs mainly through buckling of stems in the lowest levels of the crop as the plants dry out and weaken late in the season. This mechanism is very different to that described for trees and cereals where lodging occurs due to the action of the wind and the resulting lateral displacement of the upper parts of the plants. It is therefore likely that methods used to improve standing ability of pea crops may be different from those used for cereals and trees.

The required properties of plant stems, regarding their role in support, were summarised by Wainwright *et al*, (1976):

a) Stems should transmit or carry a force over the necessary distance.
b) Stems should neither break nor deform excessively.
c) Stems should be able to cope with exceptional loads due to accident or extreme conditions.

d) Stems should use the least amount of material necessary to provide the support required.

In the wild, pea stems meet these criteria by using plants of other species for support. This is not possible for pea plants grown as a monoculture in a crop, and so, without the extra support, the plants fall over.

A comparison of the flexural rigidity, ($Y.I_g$), and (M_{max}) of basal portions of pea stems with published values from Tani (1963) and Oda *et al* (1966) for wheat, barley, and rice stems is given in table 2.8. For the varieties studied ($Y.I_g$) is more than an order of magnitude greater for cereals than for peas. The values given for (M_{max}) show that even the strongest pea stems tested (from the variety Progreta) were 50% weaker than the weakest cereal stems found by Tani or Oda *et al*.

Grace and Russell (1977) found that Young's modulus of *Festuca arundinacea* leaves was dependent upon growing conditions. (Y) was almost doubled by subjecting plants to continuous wind or drought. The major structural changes to the leaves were an increase in the silicate content and the amount of schlerenchyma. In the present study measurements were only made on plants grown under glasshouse conditions, with no water shortage and little disturbance. It is possible that the values of (Y) found for the samples used in this study are lower than those that might be found in plants grown in the open.

Table 2.8 Values of flexural rigidity ($Y.I_g$) and breaking moment (M_{max}) for rice, wheat, and barley stems from Tani (1963) and Oda *et al* (1966), and samples from the base of pea stems from the varieties studied above.

	$Y.I_g$ (N mm²)	M_{max} (N mm)
This study		
Pea stems	127 to 751	3.8 to 16.4
Tani (1963)		
Rice	8044 to 14421	57.3 to 111.4
Wheat	14421 to 16775	52.6 to 99.7
Barley	8535 to 15500	36.1 to 105.2
Oda *et al* (1966)		
Wheat	7550 to 13538	31.4 to 113.3
Barley	5984 to 19620	23.3 to 153.0

Future studies should measure (Y), (I_g) and (M_{max}) for many varieties and cultivars to establish what potential exists amongst currently available genotypes, and to see how stem strength and rigidity varies with stem structure. The variation of these attributes with time (leading up to canopy collapse) and growing conditions also requires investigation.

Most fresh mass was found to be concentrated into the upper canopy. Whilst this obviously does not improve the overall stability of the crop, the importance of its role in lodging is unclear, given that buckling of stems appears to be the principal mechanism in lodging of pea crops.

Results and calculations showing the water carrying capacity of different phenotypes demonstrate that rain water may add significantly to the weight of the canopy especially in leafless varieties. Water carrying capacities of leaves, stems and tendrils will be affected by any damage to their surface waxes. Thompson (1974) showed disruption of the surface waxes on the leaves of *Festuca arundinacea* due to abrasion by neighbouring leaves moving in the wind. Other reports (see Grace, 1977) have included damage due to the folding or tearing of leaves, and the impaction of wind-blown particles. It should be remembered, however, that leaves inside pea crops are not free to move as they are rigidly connected through their

tendrils to neighbouring plants. It thus seems unlikely that the surfaces of leaves from field grown pea crops suffer major disruption, and hence they may be expected to have similar water carrying capacities to leaves from greenhouse grown plants.

Improvement of the gross structural characteristics of the stem would certainly improve standing ability. Snoad (1980) comments that thicker stems tend to be rather weak, probably due to enlargement of the central cavity, and hence there has been a tendency to avoid plants with such stems in preference to those with the 'required thin type of stem'. It is clear from equations 2.1 and 2.2, let alone the results shown above, that this approach to breeding for plants with stiffer, stronger stems is seriously flawed. For a given amount of material in the walls of a cylinder (I_g) increases as the outer diameter of the stem increases. Accordingly the load necessary to cause buckling or deflect the end of a beam by a given amount increases as (I_g) increases. Neenan and Spencer (1975) found that resistance of wheat and barley stems to bending was affected both by (Y) and the outer diameter of the stem.

This is not to say that thicker stems are necessarily stronger than thin ones, indeed Snoad's experiences suggest otherwise. Given the inhomogeneous nature of the tissue making up plant stems other factors - the amount of

each tissue type present and the manner in which the tissues are organised - must be considered. Also, Oda *et al* (1966) found high values of (I_g) in some varieties of wheat and barley with comparatively thin stems, due to thickening of the stem wall and a reduction in the size of the central cavity within stems. It does demonstrate, however, that before a plant with a thick stem is rejected out of hand from the breeding programme the stem should be examined in detail, both with respect to the characteristics studied here and its finer detail. For a breeding programme that was innovative enough to introduce the leafless and semileafless phenotypes it seems strange that thicker stemmed plants have not been investigated in more detail.

Other changes that could improve standing include reducing the amount of material supported by each stem and increasing planting density (thus introducing more stems and petioles into the canopy). It is not certain that either of these modifications could be made to work successfully as other factors, relating to yield and competitive relationships between plants, must be considered. The effect of reducing canopy height, so successfully used in the breeding of varieties of cereals with better standing ability, depends on the precise mechanism of lodging. If the principal mechanism of lodging in dried pea crops is buckling of main stems low

in the canopy, any improvement due to a reduction in canopy height will be a consequence of a reduction in the total amount of plant matter present.

Precision of estimates for (Y) using the method above seems to be quite low. This is probably due to a combination of three factors:

i) Natural variation between individual plants.

ii) Different rates of drying between plants.

iii) Errors in the measurement of the length of stem or petiole, (l), deflection of the end of the sample, (D), and (I_g).

Given the extent of variation seen amongst plants in (M_{max}), it seems likely that most of the variation in (Y) is due to factors (i) and (ii).

CHAPTER 3

MOMENTUM ABSORPTION BY DRIED PEA CROPS

INTRODUCTION

The examination of the momentum absorption characteristics of semileafless, leafless, and conventional pea crops is of particular interest as it offers the chance to assess the effects of variation in the total amount of plant material present, and altered leaf morphology, in crops that are similar in height and, in many ways, overall design. It is to be expected that the observed differences in canopy density (as shown in the last chapter) will have an effect upon canopy ventilation. Also, reduction of leaf size may be expected to lower the boundary layer resistance around the leaves of such plants (see Grace, 1980), improving the coupling between leaves and atmosphere. Differences in the microclimate between such varieties have already been reported with respect to light interception (Pyke, 1983).

The methods most often used for studying momentum absorption are eddy correlation and the measurement of wind profiles. The flux-profile relationships developed for wind profiles (see below and Thom, 1975) allow calculation of the drag per unit area, effectiveness of

momentum absorption, etc. for crops and other types of surface. Recently, however, the use of methods dependent upon flux-profile relationships has come under criticism (eg. Legg and Monteith, 1975; Finnigan, 1985), most especially for work on forests. Zero-gradient and even counter-gradient fluxes have been reported (eg. Denmead and Bradley, 1985). Criticism of these methods in relation to arable crops is, however, limited, and has concentrated largely upon the precautions that must be taken to ensure that accurate measurements are made within the fully adjusted zone of the boundary layer.

Shaw (1982) comments that studies relating mean wind-speed to lodging are of little use, as the principal agents in this process are likely to be localised gusts occurring at specific weak points in a crop. Further, in previous studies, it has been shown that other factors related to wind need to be introduced when considering the importance of wind on lodging. For instance, it is known that resonance of plant stems can result from the passage of eddies at the natural frequency of the plants in a crop (Inoue, 1955), and that this can play a major part in lodging (Milne, 1986). Whilst all this is true for trees or cereal crops, in which lodging is a fairly rare event it is possibly not so true for the pea crop. The large number of intimate connections between plants (see chapter 2) will cause the momentum absorbed from powerful, but isolated gusts to be dissipated over a wide area. Motion

of any plant within the pea crop will be damped to a greater or lesser extent by all plants that it is connected to, directly or indirectly. Hence spatial effects on canopy collapse in peas are likely to be minimal. Given that pea crops (other than some leafless varieties) will not remain erect throughout the whole season under any circumstances it may well be more appropriate to consider the action of wind not as the principal agent in canopy collapse but as a load on the crop structure additional to that from other sources.

THEORY

Above canopy wind profiles

As air moves over a surface (be it the sea, desert, forest, or whatever) particles close to the surface are slowed down through the action of viscous forces. Molecules brought into contact with the surface adhere to it and have zero velocity for an instant. Molecules moving over this layer are slowed down through their interaction with the particles in contact with the surface. This type of interaction establishes a profile of increasing wind-speed with distance from the surface and results in an effective vertical exchange of horizontal momentum between levels of higher wind-speed and those closer to the surface.

For an extensive, level, and uniform crop, variation of wind-speed with height is shown in figures 3.1(a) and 3.1(b), and described by the familiar equation:

$$u(z) = \frac{u_*}{k} \ln \frac{z - d}{z_0} \qquad 3.1$$

where $u(z)$ = wind-speed at height (z)
u_* = eddy (friction) velocity
k = von Kármán's constant
d = zero plane displacement
z_0 = roughness length

Von Kármán's constant (k) is independent of surface type. Empirically derived values over the range 0.35 to 0.435 may commonly be found in the literature (Yaglom,1977). Monteith (1973) gives a value of 0.41 as the mean of the most reliable field determinations.

(d) is introduced into the equation only when dealing with surfaces that include elevated roughness elements (eg. plants). For measurements over surfaces that lack such elements (d) is omitted. (z_0) (or ($d+z_0$) where (d) is included) is the level at which the logarithmic wind profile predicts zero wind-speed. The physical meaning of (z_0) is often given as being the size of the smallest turbulent eddy passing over the surface (eg. Miranda, 1982).

Equation 3.1 is only true for conditions of neutral stability. This condition exists when temperature decreases away from the earth's surface by $-0.01°C\ m^{-1}$ (the dry adiabatic lapse rate, see McIntosh and Thom (1969) and

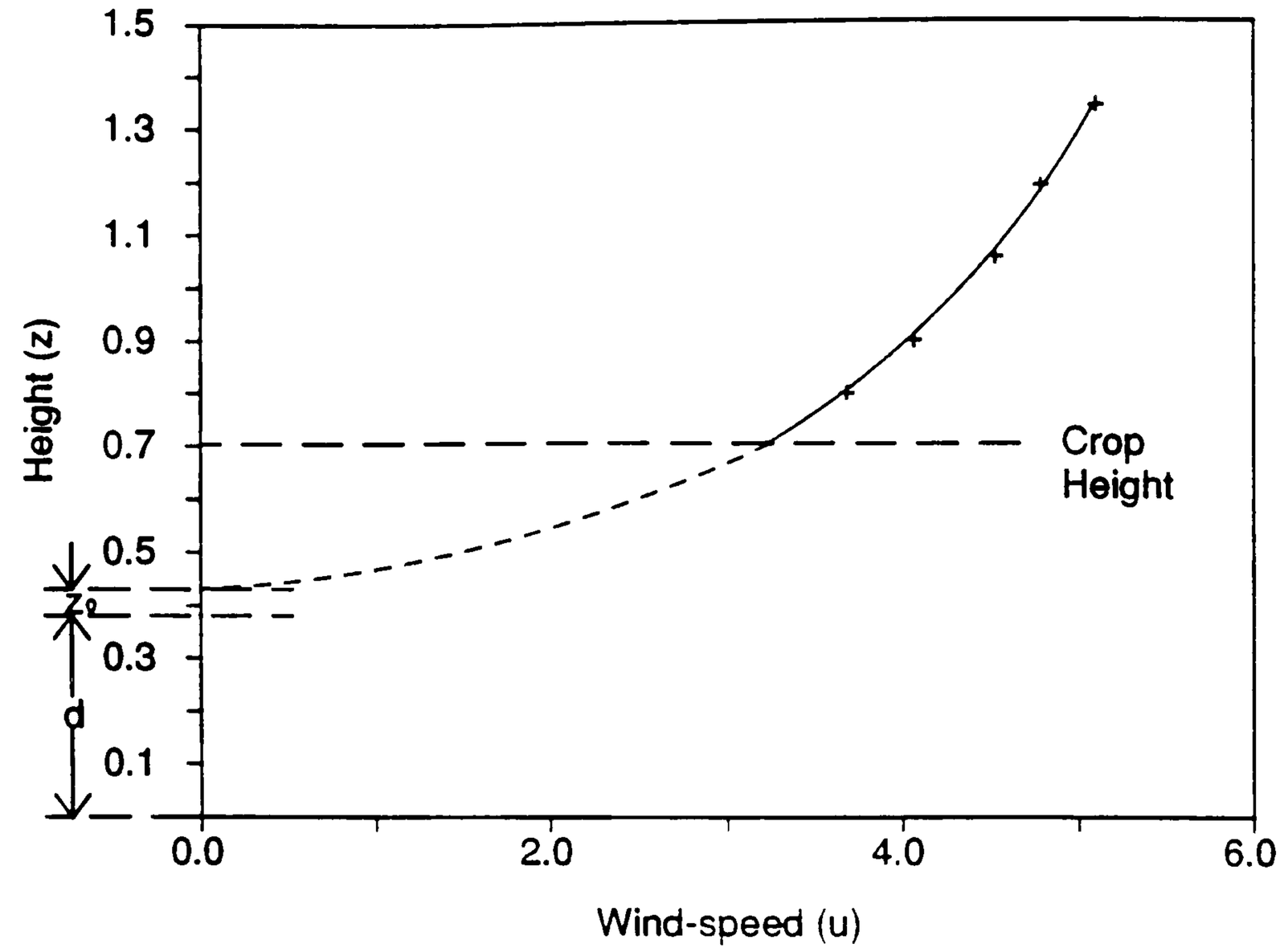


Figure 3.1 a) Specimen profile from measurements over the variety Maro at growth stage (vi) (see below) with conditions close to neutral. Equation 3.1 predicts zero wind-speed at a height $(d+z_0)$, as shown by the line (-----). However, within the canopy this relationship does not hold, and variation of wind-speed with height must be described in other ways (see below).

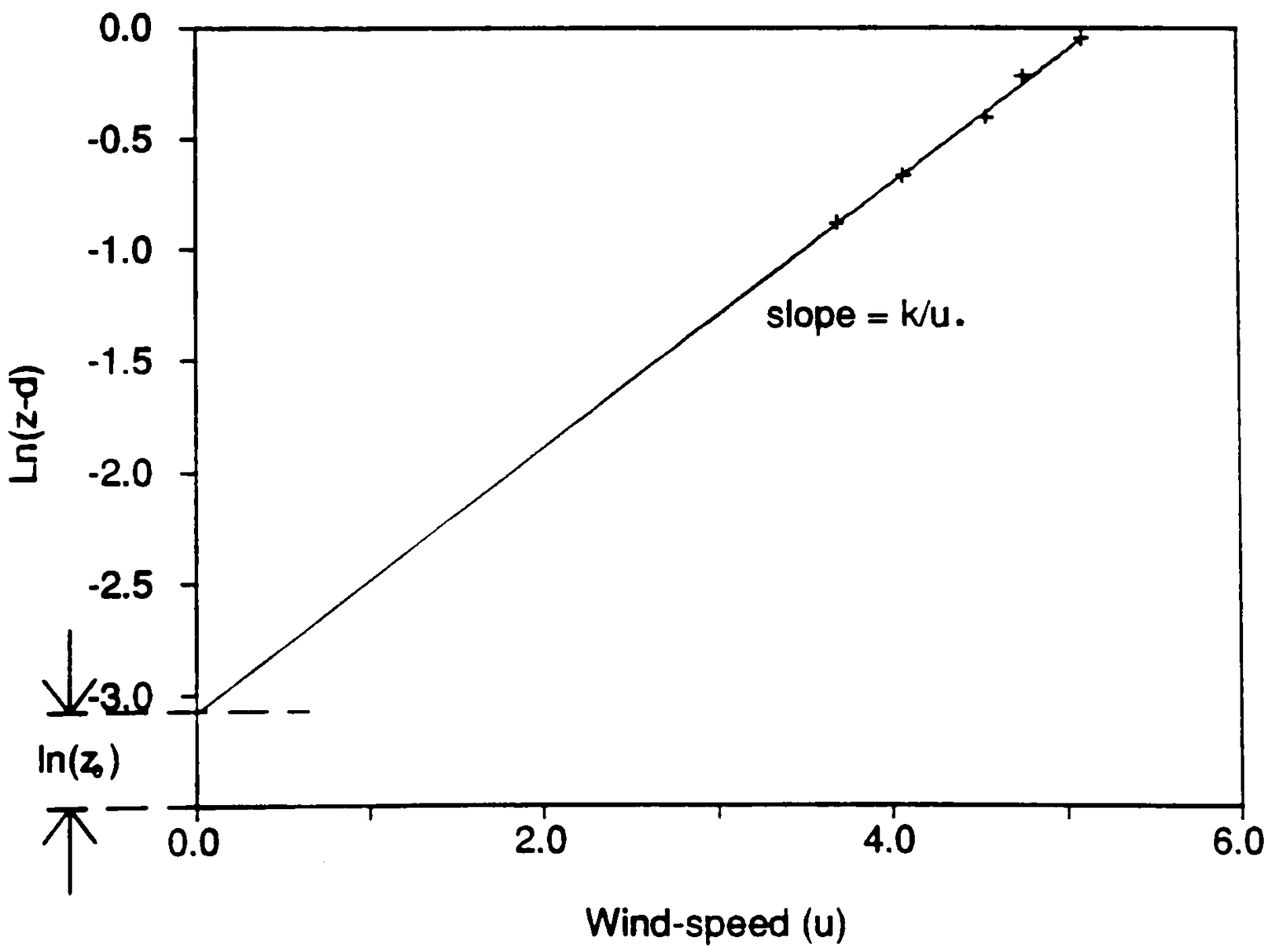


Figure 3.1 b) Data from figure 3.1a plotted to show the log-linear wind profile, allowing calculation of (z_0) and (u_*).

any other textbook of meteorology), the negative sign denoting a reduction of temperature with height. During the day, heating of the earth's surface by the sun causes unstable conditions to arise (temperature decreasing with height by more than $-0.01°C\ m^{-1}$), where the upwards motion of warmed parcels of air is enhanced. At night, cooling of the earth's surface results in inversion, or stable conditions to exist, where vertical motion within the airstream is restrained. The effects of enhancing or restraining vertical movement of air upon profile shape are given in figure 3.2 (see Sutton, 1953; Thom, 1975), from which it is clear that account needs to be taken of atmospheric stability when measuring profiles. It is worth noting, however, that, as shown in figure 3.2, close to a surface the effect of non-neutral stability conditions is often small.

The wind counteracts bouyancy effects through disruption of rising eddies by its turbulent flow. Windflow and temperature gradient are related in the dimensionless Richardson number, (Ri):

$$Ri = \frac{(g/T_a).(d\theta/dz)}{(du/dz)^2} \qquad 3.2$$

where g = acceleration due to gravity
$d\theta/dz$ = gradient of potential temperature
T_a = absolute temperature at a level defined by

$$z_a = (z_1 . z_2)^{1/2}$$

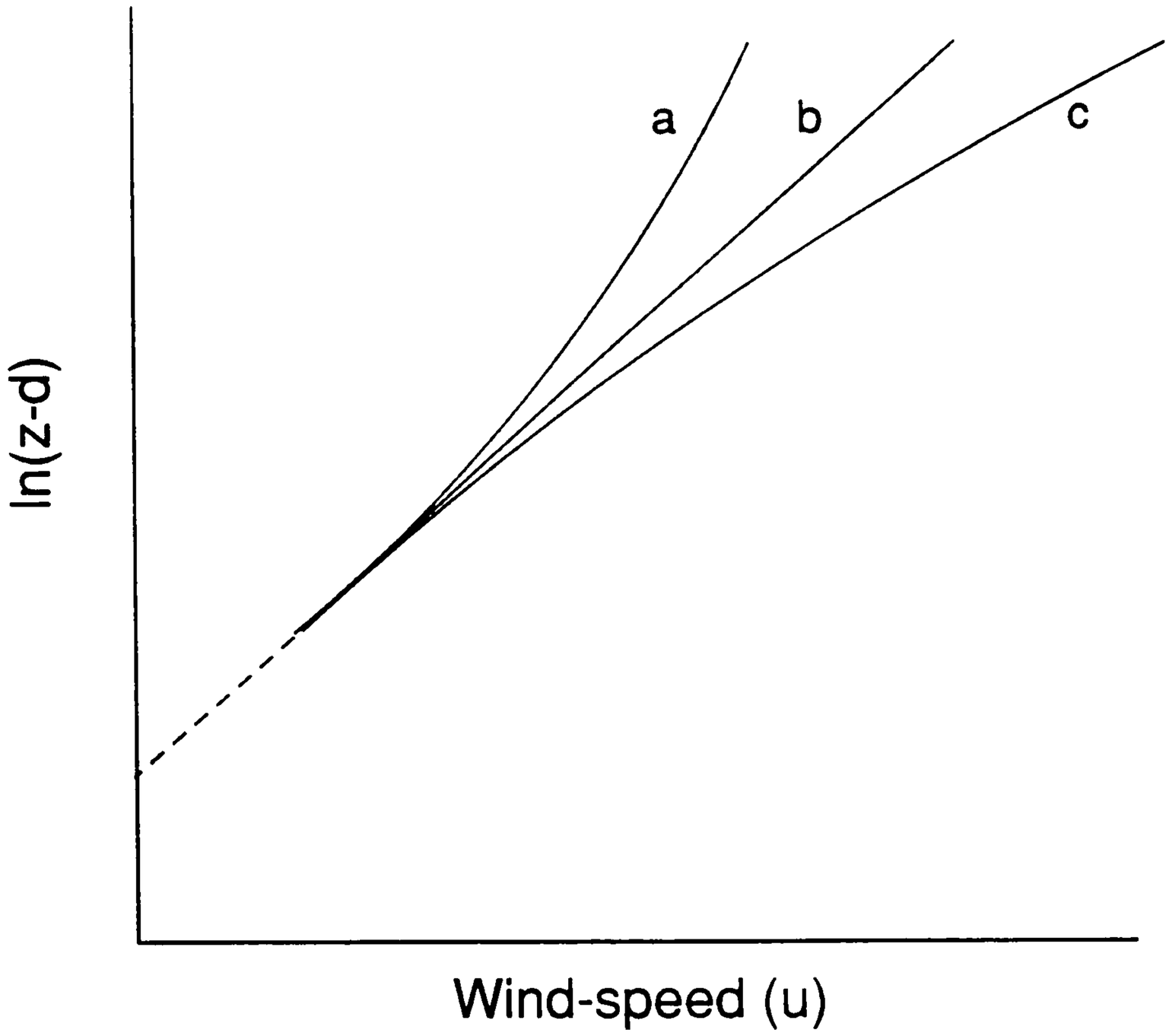


Figure 3.2 Effects of different stability conditions on the shape of the wind profile.

a) Profile for unstable conditions ($dT/dz < -0.01$ °C m^{-1})

b) Profile for neutral conditions ($dT/dz = -0.01$ °C m^{-1})

and c) Profile under stable conditions ($dT/dz > -0.01$ °C m^{-1}).

Close to the ground (Ri) may be calculated using the temperature gradient, dT/dz, in place of $d\theta/dz$ (Rosenberg, 1974). (Ri) is negative for unstable conditions and positive for stable conditions.

The Monin-Obhukov stability length (L) is also used to describe atmospheric stability:

$$L = -\frac{\rho c_p . T . u_*^3}{k . g . H} \qquad 3.3$$

where ρ = density of air
c_p = specific heat of air at constant pressure
H = flux density of sensible heat in air

If the value of (Ri) in a layer of air exceeds +1 the restraint on vertical motion is such that it is impossible for turbulence to arise in the air stream, and any eddies produced elsewhere that enter this region will rapidly die out (see McIntosh and Thom, 1969). In practice, however, (Ri) need only be equal to about +0.25 (corresponding to a strong temperature inversion with low horizontal wind-speeds) for motion to be virtually laminar and vertical mixing to be almost completely absent.

A negative (Ri) of only -0.10 is capable of significantly altering the shape of a wind profile. As (Ri) is reduced further, free convection replaces forced as the dominant transfer mechanism, with the resulting enhancement of vertical motion. For (Ri) less than -1 (corresponding to very strong convective instability with low horizontal wind-speed) free convection alone is present (Oke, 1978).

For accurate determination of wind profile parameters it is thus important to know for what range of (Ri) equation 3.1 can be relied upon. McIntosh and Thom (1969) give only the very narrow range of $-0.01 < Ri < +0.01$ outside which consideration of the stabilty conditions becomes necessary.

To allow for a wider range of stability conditions Paulson (1970) incorporated into equation 3.1 a correction term, (ψ):

$$u(z) = \frac{u_*}{k}\left(\ln \frac{z - d}{z_0} - \psi_1 \right) \qquad 3.4$$

Despite a lack of rigorous theory on stability correction, there has been some general agreement with the flux-profile relationships of Dyer and Hicks (1970). Miranda (1982) used these relationships to derive the following expressions for (ψ_1):

$$\psi_1 = 2.\ln[(1+'x)/2]+\ln[(1+'x^2)/2]-2.\tan^{-1}('x)+\pi/2 \qquad 3.5$$

for unstable conditions, where

$$'x = [1-16.(z/L)]^{1/4} = [1-16(Ri)]^{1/4} \qquad 3.5\ a$$

and

$$\psi_1 = -5.(z/L) \qquad 3.6$$

for stable conditions.

Using values of (d), (z_0) and (u_*) calculated from profiles it is possible to calculate the values of a number of other parameters. Thom (1972) gives the following relationships for (τ), the shearing stress:

(a) (b) (c)

$$\tau = \rho u_*^2 = \rho u(z)^2 C_D(z) = \rho' u^2 S_d \bar{C}_d / p_d \qquad 3.7$$

where $C_D(z)$ = bulk drag coefficient referred to level (z)
$'u$ = hypothetical uniform wind-speed within canopy to give the same drag as the canopy wind profile
S_d = cumulative area of vegetation per unit horizontal area
$\bar{C}_d$ = drag coefficient for an average canopy element at wind-speed (u)
p_d = shelter factor for momentum such that (C_d/p_d) is the effective drag coefficient for an average element within the canopy.

These relationships demonstrate not only how (τ) may be calculated from profile data (as in 3.7 a), but also that (τ) is dependent on the characteristics of the surface in question, such as drag coefficients of canopy elements.

Assuming that no drag is transmitted to the ground (τ) may also be described as (Thom, 1971; Landsberg and James,1971):

$$\tau = \rho \int_0^h [u(z)^2 . A(z) . \bar{C}_M(z)] . dz \qquad 3.8$$

where A(z) = area per unit volume at height (z)
$\bar{C}_M(z)$ = effective drag coefficient at level (z)

A variation on this equation is used to predict values of (τ) from wind-tunnel determinations of drag coefficients of isolated canopy elements in the next chapter.

The bulk canopy drag coefficient for a level (z) may be calculated from

$$C_D(z) = \frac{u_*^2}{u(z)^2} = \frac{k^2}{(\ln[(z-d)/z_0])^2} \qquad 3.9$$

The derivation of these quantities and others, and further inter-relationships between them are discussed in detail by Thom (1975).

Within canopy profiles

Close to the surface and within a canopy the log-linear profile no longer holds (see figure 3.1 a). Several exponential relationships have been proposed, the commonest of which is probably (from Inoue, 1963; Cionco, 1965):

$$u(z) = u(h).\exp[\beta(z/h-1)] \qquad 3.10$$

where β = an extinction coefficient
$u(h)$ = wind-speed at crop height.

Subsequent work by Cionco (1972, 1978) showed a good fit for this equation, and found values of (β) from 0.44 for a citrus forest, through a range of 1.3 to 2.8 for agricultural crops to 4.4 for a gum forest.

Non-exponential relationships include that of Thom (1971):

$$u(z) = u(h).[1+\alpha(1-z/h)]^{-2} \qquad 3.11$$

Landsberg and James (1971) found that wind profiles within a spruce forest were described much more accurately using expressions including the cumulative leaf area index (S):

$$u(z) = u(h).[1-a.\exp(-b/S(z))] \qquad 3.12$$

$$u(z) = u(h).(1-a[S(z)/(S(z)-b)]) \qquad 3.13$$

where (a) and (b) are both empirical coefficients.

Influence of wind-speed on (d) and (z_o)

Behaviour of the zero plane displacement (d) and the roughness length (z_o) with a change of wind-speed has been a matter of discussion for many years. Makkink and van Heemst (see Rosenberg, 1974, p. 105) showed, in a review, the reported variation in (d) and (z_o) for wind-speeds between 0 and 6 m s^{-1} for rice, sorghum, and barley. In all three species (d) followed a similar pattern, increasing to a peak and then levelling out or decreasing. (z_o), however, responded differently between species. Its value for sorghum was fairly constant. For the rice crop, however, the value quadrupled as wind-speed increased from 1 to 3.5 m s^{-1} and then decreased to its original value. Monteith (1973) ascribes these changes to streamlining of

canopy elements, to large scale deformation of the canopy, and to a decrease in drag coefficient with increased wind-speed. Results from a number of authors, however, show that there is no concensus on this issue (table 3.1). The results of Oliver and Mayhead (1974) are perhaps of special interest as both parameters were independent of wind-speed over a wide range of up to 17 m s^{-1}. It is also interesting that different responses have been reported for the same crop species (eg. the studies on soybeans by Perrier *et al*, 1972, and by Baldocchi *et al*, 1983).

Taking (d) as the mean level of momentum absorption within a canopy (Thom, 1971; Jackson, 1981; Raupach and Legg, 1984) we must expect that any change in the structure of a crop (due, for example to branches, leaves, or heads of cereal plants being swept back by the wind) will lead to a change in (d). Similarly, such action should affect the apparent roughness of the crop. It seems clear, however, from table 3.1 that in many cases any such change is minimal.

Profile measurement

Profiles are often measured with an array of cup anemometers supported at several heights above the crop or surface in question. However, it has been known for many years that this type of anemometer is prone to potentially large errors when measuring a natural airstream. As early as 1923 Sabinin reported an overestimation of 10%, whilst

Table 3.1. Some reported effects of increased wind-speed on the zero plane displacement (d) and the roughness length (z_o). An asterisk denotes that the effect was dependent on the wind regime.

Author	Crop	d	z_o
Uchijima (1976)	corn	down	up
Bache and Unsworth (1977)	cotton	up/down*	up/down*
Leuning and Attiwill (1978)	eucalyptus	independent	independent
Thom (1971)	field beans	down	down
Maki (1969)	maize	down	up
Tani (1963)	rice	up/down*	up/down*
Oliver and Mayhead (1974)	Scots pine	independent	independent
Perrier *et al* (1972)	soybean	up	down
Baldocchi *et al* (1983)	soybean	independent	independent
Munro and Oke (1973)	wheat	independent	independent
Legg and Long (1975)	wheat	independent	independent

Schrenk (1929) calculated that errors up to 30% were possible. Such work prompted improvements in anemometer design (eg. Marvin, 1934; Scrase and Sheppard, 1944; Jones, 1965). Despite this effort, Izumi and Barad (1970) found 10% errors in cup anemometers, in comparison with hot wires and sonics. Hogstrom (1974) reported similar results, though Hyson (1972), under conditions of neutral stratification only found an error of between 1 and 3%. Combining these and other results into theoretical analyses, Ramachandran (1969) and Kaganov and Yaglom (1976) showed that two sources of error were present:

i) u-error, resulting from a faster response of the cup assembly to acceleration than deceleration, and

ii) w-error, due to a response to the normal velocity component (that component perpendicular to the one being measured), (see MacCready, 1966).

These errors are additive for cup anemometers (Wyngaard, 1981). Propellor and vane anemometers, however, have a cosine-type response (albeit generally non-perfect) to off-axis winds (Pond *et al*, 1979; Teunissen *et al*, 1985). Over-running due to u-error will be opposed by the response to the normal velocity component. For general micrometeorological work using such sensors, correction factors may be employed to eliminate the limitations of the cosine-type response (eg. Bowen and Teunissen, 1986).

Another source of error arises through flow distortion by the mast used to hold the anemometers (Rider, 1960; Dyer, 1981), hence care must be taken in design, especially where upwind fetch is limited and sensors are close together.

A number of largely empirical relationships dependent on a 4/5 power law have been proposed to allow estimation of boundary layer depth. Assuming only the lowest 10% to be fully adjusted (Peterson, 1969), Munro and Oke (1975) proposed that, for a fetch (x), the useful boundary layer depth (δx) should approximate to:

$$(\delta x) = 0.1.(x)^{4/5}.z_0^{1/5} \qquad 3.14$$

This should not be taken as any more than a general guide, especially for experiments with little upwind fetch.

Calculation of profile parameters

Methods for evaluating (d), (z_0) and (u_*) from profile data involve systematically altering the value of (d) between limits of, say, 0.4.(h) and 0.85.(h) (h = crop height) until a straight line relationship is found between ln(z-d) and wind-speed (see equation 3.1). It is then a simple matter to find ln(z_0) (as the y-intercept) and (u_*), (as (k)/slope). The most popular approaches are the least squares method (Robinson, 1962; Stearns, 1970; Miranda, 1982), and the use of relationships such as:

$$(u_3-u_2).\ln\frac{(z_2-d)}{(z_1-d)} = (u_2-u_1).\ln\frac{(z_3-d)}{(z_2-d)} \qquad 3.15$$

from Landsberg and Jarvis (1973).

Given the errors inherent in wind-speed mensuration both methods have been assessed for their sensitivity to error. A comparison of the two (see appendix III) showed them to have roughly similar sensitivity, though the least squares method did emerge very marginally more accurate and was accordingly the one used. The required accuracy of anemometer readings was found to be 1% or better. Fortran77 programmes for both methods are also shown in appendix III.

MATERIALS AND METHODS

Profiles were taken over and within the three field plots containing the varieties Filby, Filigreen and Maro, described in the previous chapter. The dimensions of these plots were (see also figure 2.3):

Maro (conventional)	285 m	by	100 m
Filigreen (semileafless)	100 m	by	100 m
Filby (leafless)	100 m	by	85 m

The maximum fetch (with wind blowing diagonally across the plots), is somewhat more than the longer dimension given in each case. The minimum fetch is a few metres less than

the shorter dimension, given that it was considered undesirable for the anemometers to be sited right at the edge of a plot.

After studying results and observations from a preliminary field season in 1983, a decision was made to take a series of measurements over each canopy at roughly the same stages of growth, due to differences in the rate of development for the varieties used. The stages were, approximately,

i) 2 leaves fully expanded
ii) 5 leaves fully expanded
iii) 9 leaves fully expanded
iv) Flowering
v) Pod filling
vi) Canopy drying (still standing)
vii) Canopy collapsing

Dates of measurement, and the number of profiles taken at each 'growth stage' are given in table 3.2.

For each stage between 20 and 30 half hourly profiles were measured above the canopies using the Vector cup anemometers and LEDA vane anemometers. Also at stage vi (canopy drying but still standing) 30 half hour profiles were measured within the canopies using the LEDA vane anemometers. To reduce errors resulting from differences

Table 3.2 Dates of profile measurement in 1984 and numbers of half hourly profiles taken.

Variety	Growth stage	Dates	N
Filby	1	24, 25 April	21
Maro	1	26, 27 April	30
Filby	2	3, 4 May	22
Filigreen	2	8, 9 May	20
Maro	2	9, 10 May	22
Filigreen	3	21, 22 May	20
Filby	3	24, 25 May	22
Maro	3	28, 29 May	30
Filigreen	4	1, 4 June	25
Maro	4	5, 6 June	25
Filby	4	7, 8 June	22
Filigreen	5	11, 12 June	25
Maro	5	13, 14 June	27
Filby	5	14, 15 June	25
Filby	6	25, 26 June	21
Maro	6	26, 27 June	25
Filigreen	6	27, 28 June	23
Filigreen	7	5, 6 July	22
Maro	7	9, 10 July	30
Filby	7	26, 27 July	23
Within canopy profiles*			
Filigreen		27, 28 June	30
Maro		5, 6, July	30
Filby		9, 10, 11 July	30

* Ten profiles were measured at each of three sites in each variety to reduce error through localised variation.

in local canopy structure three sets of ten within canopy profiles were taken for each variety at different sites within the plots.

No profiles were measured over Filigreen for stage (i). The final set of profiles (vii) for the leafless crop were taken whilst it was still erect, as it did not collapse until just before harvest (see chapter 2).

Above canopy profiles were measured both with an array of six Vector A100R 3-cup anemometers (Vector Instruments, Rhyl, Clwyd), and an array of six LEDA 1000 vane anemometers (Lowne Instruments Ltd., London).

Unfortunately, due to technical problems, results are not available from the vane anemometers for much of the early part of the season. However, from comparison of available results with those from the Vector anemometers (appendix VI), the LEDA anemometers were found to be suitable for profile measurement. They were, accordingly used to measure within canopy profiles (being smaller, and hence less disruptive to both airflow and canopy, than the cup anemometers). Output from the cup anemometers was recorded using six mechanical counters, read manually at half hourly intervals, whilst that from the vane anemometers was recorded using a Campbell CR21 data logger (Campbell Scientific, Logan, Utah).

Wind direction was monitored with a Porton wind-vane (Vector Instruments, Rhyl, Clwyd). Temperature, and temperature gradients within profiles were monitored with thermistors and three pairs of differential thermocouples. These sensors were monitored by a second CR21 data logger and were powered from a 12 V lead-acid battery. All equipment used in profile mensuration is described in greater detail below.

Instrumentation

Data acquisition

Output from all instruments apart from the cup anemometers was recorded by two CR21 data loggers. These have seven analogue input channels for monitoring in either a millivolt range (-2.0 to 25 mV with 5 μV resolution) or a volt range (-0.2 to 2.5 V with 1 mV resolution), and two pulse counting channels. On the model used for this work channels are scanned every 10 seconds. For storage of data a number of statistical functions are available, of which means, standard deviations, maxima, minima and spot readings, all at pre-defined intervals were used.

Connections to the loggers were as follows:

Logger 1.

a) 6 LEDA vane anemometers were connected to analogue channels 1 - 6 in their Volt range. 10 minute means, maxima, minima (both as a check on anemometer operation, and also to detect periods when wind-speed was less than 1 m s^{-1} and unreliable for profile determination) and standard deviations were taken.

Logger 2.

a) Three pairs of copper-constantan thermocouples (after amplification) were connected to analogue channels 1 - 3 (mV range). Again, 10 minute means, maxima, minima and standard deviations were recorded.

b) A thermistor, powered from the 2 V excitation facility of the logger and connected to analogue channel 4 (mV range). Temperature is calculated by the logger using a 5th order polynomial. Data were recorded with the same functions as were used for the thermocouples.

c) The Porton wind-vane was connected to analogue channels 5 and 6, in the Volt range. Due to the nature of the output from this instrument (see below), it was impossible to take mean values and spot readings were taken every minute instead.

Instrumentation masts

Two masts were made, one for the vane anemometers and the wind-vane, and the other for the cup anemometers and the thermocouples. Both masts were made from 2 cm diameter

aluminium tubing, and were 2 m tall. To hold them steady each mast was guyed down using thin, strong, cord, pegged down firmly with stakes 30 cms long. Side arms were attached to the masts using laboratory clamps. These side arms were 50 cms long, made from the same 2 cm diameter tubing as the masts. To make the vane anemometer mast more rigid (bearing in mind the cosine response of these instruments) a second 2 m mast was clamped to side arms after examination of early results revealed problems with the alignment of these sensors. The cup anemometers and the wind-vane were both firmly screwed onto their side arms. The vane anemometers were secured with clamps. A major concern was the spacing between anemometers. This was limited by the fetch available (see above). From the published relationships between fetch and boundary layer depth the maximum thickness of the fully adjusted boundary layer would not be much in excess of 1 m. Accordingly the anemometers on both masts were arranged alternatively either side of the mast on their 50 cm side-arms with cups/vanes held above the canopy under examination in a layer little more than a metre deep. Due to the limited space available, anemometers were evenly spaced up the mast, rather than in the logarithmic manner more widely used in such studies. It is to be hoped that any errors resulting from anemometers interfering with one another, or anemometers being exposed outside the fully adjusted boundary layer would be picked up by the method used for calculation of profile parameters (see below).

It is possible to increase the separation between anemometers by using side-arms of variable length, or by attaching each anemometer to its own, individual, mast (allowing the anemometers to be spread out in a line at different heights). Both approaches were tried in the preliminary field season in 1983, and both, unfortunately proved unsuccessful. The biggest problem was in making meaningful measurements of the height of each anemometer, due to differences in ground level (significant differences seem likely on all but the flattest of land). Given the errors to which wind-speed measurements are prone, and the sensitivity of methods of calculation of profile parameters to error, it was considered best to attach all anemometers to the same mast on side arms of similar length (albeit arranged with three on one side of the mast and three on the other). The manner in which anemometers were exposed on the two masts is shown in figure 3.3.

Anemometers

A brief comparison of the two sets of anemometers is shown in table 3.3. Whilst the very low moment of inertia of the vane assembly of the LEDA anemometers should reduce over-run (in comparison to the cup anemometers) the usefulness of these instruments in profile measurement relies heavily on their cosine response (see below).

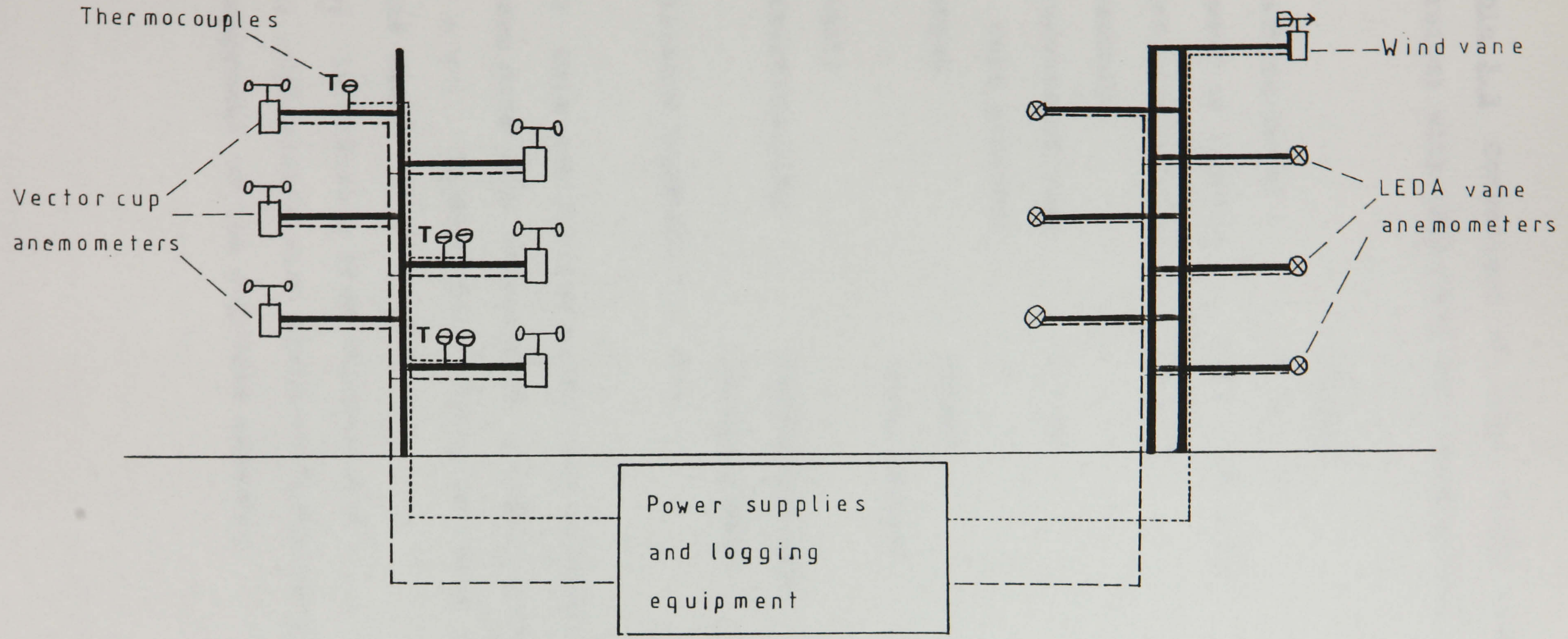


Figure 3.3 Arrangement of profile mensuration equipment in the field. Masts were 2 m tall, with 50 cm side arms, spaced evenly through a layer about a metre in depth above the crops. The two masts were sited approximately 10 m apart.

Table 3.3 Comparison of Vector A100R anemometers (3 cup version) with LEDA 1000 vane anemometers.

	Vector	LEDA [a]
Starting speed [b]	0.30 m s^{-1}	0.08 m s^{-1}
Moment of Inertia [c]	5.64 x 10^4 g mm^2	3.86 x 10^2 g mm^2
Mass of cup/vane assembly	31.43 g	1.804 g
Diameter of cup/ vane assembly	133 mm	72 mm
Output	Pulsed (reed switch)	Pulsed (chopped light)
Directionality	Omnidirectional in cup plane	Cosine-type response
Distance constant [b]	5 m	1.03 m

a) Data are for low speed vane assembly with vanes made from mica (for measurement of wind-speeds from 0.08 to 8 m s^{-1}). Higher speed aluminium vanes are available for the range 1.5 to 25 m s^{-1}.

b) Information from manufacturer.

c) Calculated with standard formulae for (I) for each component of the cup/vane assembly.

Circuit design and testing

Output from the cup anemometers was recorded by a set of 6 digit resettable counters (RS Components Ltd, Corby, stock number 259-892), powered by a 24 V rechargeable supply. These mechanical counters are too slow for the vane anemometers. As the loggers had insufficient pulse counting channels for the full set of anemometers a circuit was designed (see appendix II) to both power the instruments and to convert their output to an analogue signal using frequency to voltage converters (RS Components Ltd, Corby, stock number 307-070).

Frequency response of each converter circuit was checked using a sine-square oscillator (Type LFM2, Farnell Instruments, Wetherby, Yorkshire). Regression statistics are given in table 3.4 for the range 15 to 400 Hz (equivalent to wind-speeds from 0.12 to 10 m s^{-1}), over which all circuits gave a linear response.

The manufacturer quotes an operating range for the f/v converters of 0 to 70°C with a temperature coefficient of ± 25 ppm $°C^{-1}$. Circuit performance was tested over the range 0 to 40°C. Regression statistics are shown in table 3.5. Any adverse effect of variation in output with temperature was eliminated in practice by mounting all circuits on the same board, thus providing a similar thermal environment for all.

Table 3.4 Frequency response of the frequency to voltage converters used in processing output from the LEDA anemometers, over the range 15 to 400 Hz.

Circuit	Slope (SE) (mV Hz^{-1})	Intercept (SE) (mV)
1	7.813 (0.015)	10.75 (2.35)
2	7.771 (0.013)	12.66 (2.11)
3	7.771 (0.013)	21.33 (2.04)
4	7.732 (0.015)	17.75 (2.39)
5	7.720 (0.013)	25.26 (2.12)
6	7.649 (0.015)	23.18 (2.47)

Table 3.5 Temperature response of the frequency to voltage converter circuitry of the LEDA anemometers.

Temp(°C)	Slope (SE) (mV Hz^{-1})	Intercept (SE) (mV)
0	8.029 (0.022)	10.62 (3.42)
5	7.809 (0.013)	10.62 (2.25)
12	7.799 (0.020)	11.41 (3.47)
22	7.819 (0.017)	10.71 (2.84)
30	7.774 (0.027)	12.05 (3.97)
40	7.740 (0.015)	12.21 (2.49)

Anemometer Calibration

All anemometers were calibrated before and after the season in the wind tunnel of the Department of Forestry and Natural Resources in Edinburgh, against a pitot static tube and Combist micromanometer (Combustion Instruments, Staines, Middlesex). This instrument requires readings to be made manually. To reduce errors in the calibrations each wind-speed was calculated as the mean of 3 readings. Anemometers were mounted one at a time in the centre of the wind-tunnel, and monitored using the data logger (for the vane anemometers) and set of electro-mechanical counters (for the cup anemometers) that they would be used with in the field. Calibration data are presented in tables 3.6 and 3.7. Accuracies, expressed as the 95% confidence limit for individual predicted values from the regression, are in all cases better than 1% for a wind-speed of about 1 m s^{-1} (the lowest speed included in the calibration). From the results presented in appendix III (comparing methods of calculating profile parameters), the precision required in wind-speed measurements is about 1%. It must, however, be stressed that the structure of air flow in a wind-tunnel (constant speed, laminar) is very different to that over a field (fluctuating and turbulent). 'u-error' and 'w-error' have already been discussed (above) and are clearly of concern here. Hence results regarding accuracy and precision taken from

Table 3.6 Vector anemometer calibrations. Units for the slope in each case are (m s^{-1} [count s^{-1}]$^{-1}$), and for the intercept, (m s^{-1}). Accuracies are given as the 95% confidence limits of the lowest wind-speed used in the calibration (1 m s^{-1}). Note, however, that accuracies in the field may be seriously reduced by 'u' and 'w' type errors (see text).

a) Before field season.

Anemometer	Slope (SE)	Intercept	Accuracy (m s^{-1})
30	1.311 (0.004)	0.054 (0.016)	0.004
31	1.285 (0.005)	0.130 (0.022)	0.004
32	1.287 (0.006)	0.138 (0.027)	0.006
33	1.295 (0.005)	0.149 (0.024)	0.005
34	1.295 (0.003)	0.129 (0.011)	0.004
35	1.284 (0.006)	0.142 (0.029)	0.004

b) After field season.

Anemometer	Slope (SE)	Intercept	Accuracy (m s^{-1})
30	0.130 (0.00)	0.110 (0.024)	0.004
31	0.129 (0.00)	0.104 (0.018)	0.005
32	0.127 (0.00)	0.112 (0.014)	0.005
33	0.126 (0.00)	0.148 (0.018)	0.006
34	0.128 (0.00)	0.131 (0.021)	0.004
35	0.126 (0.00)	0.149 (0.024)	0.003

Table 3.7 LEDA anemometer calibrations. Accuracies were calculated as the 95% confidence limits of the lowest wind-speed used in the calibration (1 m s^{-1}). Note, however, that quoted accuracies are from measurements in a wind-tunnel, and that field conditions may seriously reduce accuracy through 'u' and 'w' type errors (see text).

a) Before field season.

Anemometer	Slope (SE) (m s^{-1} V^{-1})	Intercept (m s^{-1})	Accuracy (m s^{-1})
1	3.145 (0.009)	-0.022 (0.016)	0.006
2	3.065 (0.013)	0.050 (0.022)	0.007
3	3.137 (0.011)	-0.042 (0.020)	0.007
4	3.046 (0.005)	0.050 (0.010)	0.006
5	3.098 (0.006)	-0.020 (0.011)	0.006
6	3.201 (0.006)	-0.015 (0.010)	0.006

b) After field season.

Anemometer	Slope (SE) (m s^{-1} V^{-1})	Intercept (m s^{-1})	Accuracy (m s^{-1})
1	3.121 (0.010)	-0.001 (0.022)	0.008
2	3.020 (0.005)	0.020 (0.020)	0.007
3	3.119 (0.041)	-0.003 (0.054)	0.006
4	3.032 (0.014)	0.011 (0.022)	0.006
5	3.100 (0.015)	-0.041 (0.024)	0.005
6	3.248 (0.006)	0.032 (0.020)	0.006

observations in the wind-tunnel cannot be taken as more than a rough guide as to the performance of the instruments in the field.

Comparison of calibrations measured before the field season with those measured after reveal a change in calibration for most anemometers. That the calibration should change is, perhaps not too surprising, especially when considering the fact that the anemometers had not been used for prolonged periods in the field before. The results from appendix III, however, suggest that absolute values of wind-speed are not vital for the determination of profile parameters, so long as errors are similar for all anemometers. The method used to calculate profile parameters (see below) was designed to allow the removal of erroneous readings from the analysis.

The opportunity was taken of checking calibrations in the field. Once a month anemometers were mounted at the same height on a horizontal bar and run against one another.

The only problems in performance of the equipment were caused by the jack plug sockets (RS Components Ltd, Corby, stock number 478-475) used with the vane anemometers. Whilst this was noticed early in the season and rectified, some data were lost. It is recommended that better quality connectors are used with these instruments.

Cosine response of LEDA vane anemometers

Published data on comparable sensors (eg. Gill anemometers, Pond *et al*, 1979) have shown that response deviates significantly from the ideal. If cosine response differs between anemometers they will be of no use for profile measurement as the methods for calculation of profile parameters are very sensitive to error (see appendix III).

Accordingly, anemometers were mounted in the wind tunnel and rotated through angles from 0° (parallel to the axis of vane rotation) to 60° with wind-speed held steady at 3.5 m s^{-1}. Results are shown in figure 3.4. Also, in figure 3.5, a comparison is made with data from Pond *et al* (1979) for a Gill anemometer. It is clear that, despite the manufacturers claim, LEDA vane anemometers do not have an ideal cosine response. Airflow within the tunnel was checked using cotton strands in a simple flow visualisation technique to ensure that the observed deviation from ideal was due to aerodynamic characteristics of the anemometers and not to some characteristic of the tunnel. However, more importantly for profile measurement, response at each angle was the same for all anemometers (differences were very small and not consistent between angles for any pair of anemometers). It was thus decided to use these anemometers in the field, provided that some means of accurately aligning them with one another was found. This

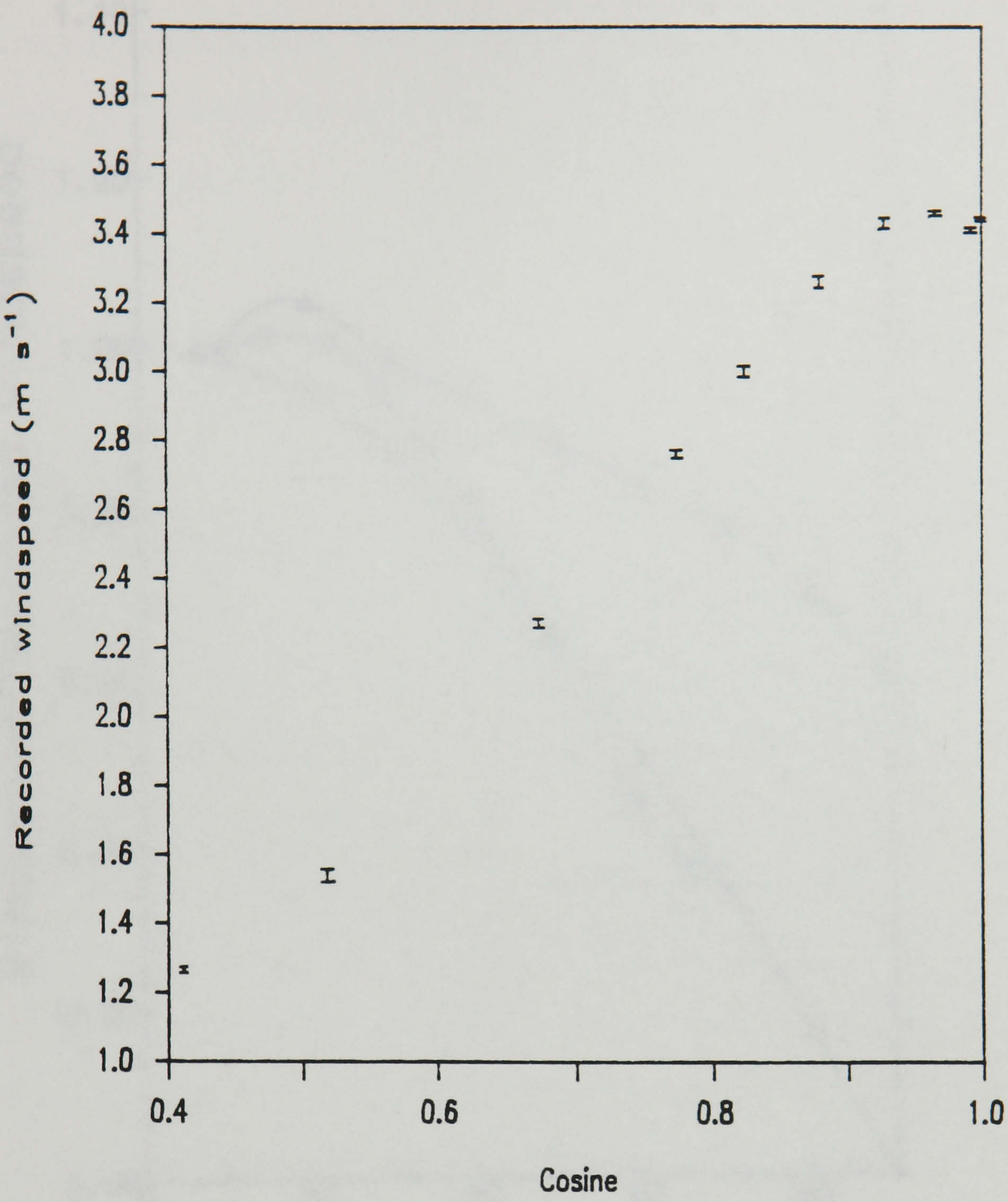
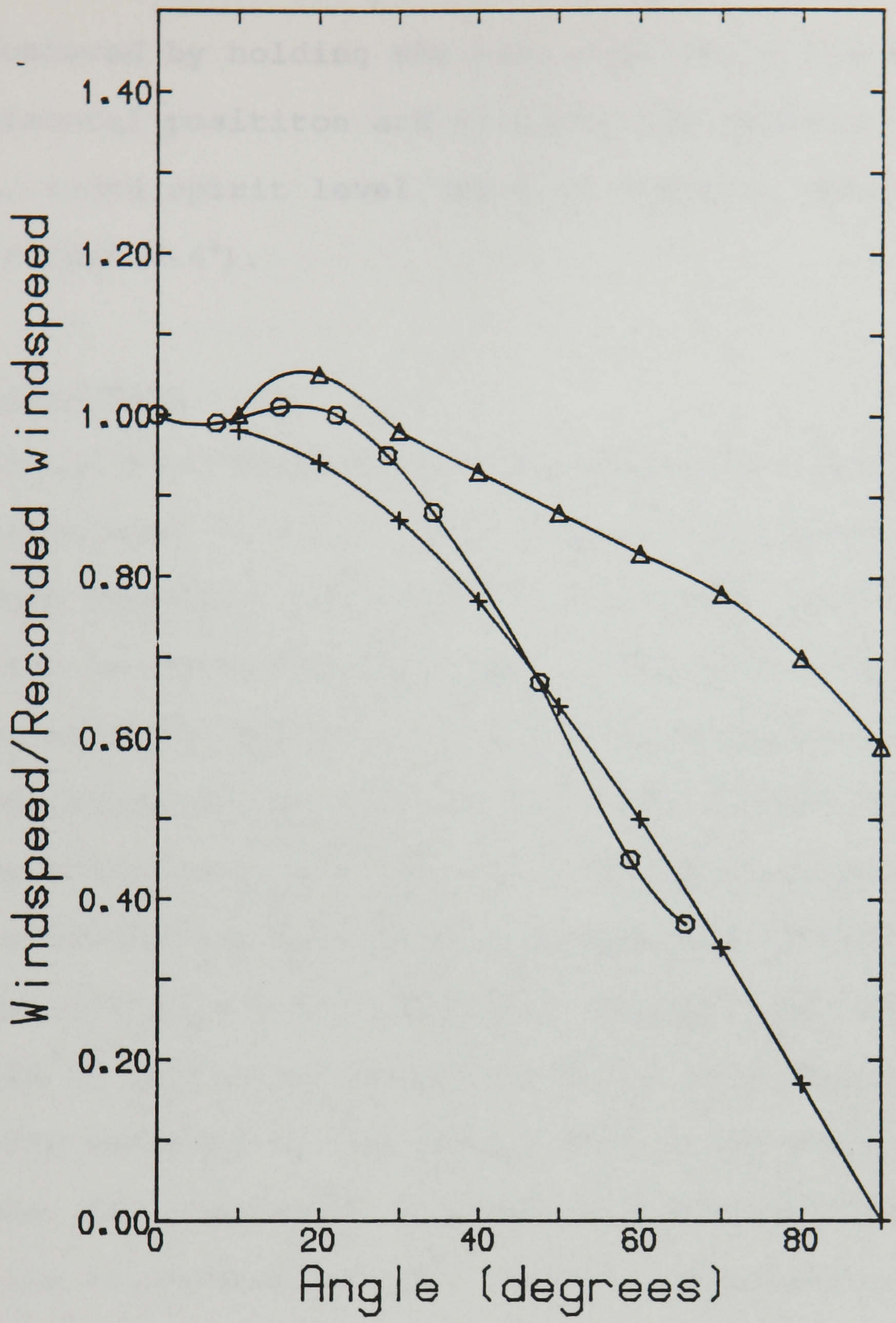


Figure 3.4 Cosine response of LEDA 1000 vane anemometers. The cosine is of the angle between the vane axis and the airflow. Error bars show the standard errors for the mean of all anemometers at each angle.



—+— Ideal cosine response

—o— LEDA 1000 vane anemometers

—Δ— Gill anemometer (from Pond et al, 1979)

Figure 3.5 Normalised wind-speed vs. angle between propellor/vane axis and the airstream. Comparison of LEDA anemometers and Gill anemometers with the ideal cosine response.

was achieved by holding the mast supporting the sensors in a horizontal posititon and aligning anemometers with a small, round spirit level (with an accuracy determined as better than 0.4°).

Wind direction

The Porton wind-vane was powered from a 12 V battery regulated down to 9.5 V. This vane has two outputs which are both dependent not only on the current wind direction but also on the direction in which the vane is swinging. After circuitry was built to regulate signals down to the voltage range of the data loggers, one channel produced a steady signal of 0.8 V or 1.6 V, whilst the second channel gave a variable signal that could be high (around 0.8 V) or low (around 1.6 V). The data loggers used are not capable of calculating wind direction from such a vane, and spot readings of the output were taken every minute instead, for subsequent analysis in the laboratory. The vane was orientated so that 'north' corresponded to the direction directly upwind of the two arrays of anemometers.

Thermometry - circuit design and testing

Three pairs of thermocouples were made from 0.06 mm diameter (48 SWG) copper-constantan thermocouple wire (Dural Plastics and Engineering, Dural, NSW, Australia). Circuits were designed using type 7650 chopper amplifiers (RS Components Ltd, Corby, stock number 303-854) in an

inverting circuit (see appendix II). An amplification of about 270 times was used for the two sets of thermocouples used for measuring temperature gradients within the profile, and of around 50 times for the third pair (used in conjunction with the thermistor to measure the reference temperature). These levels of amplification were designed to give good resolution over the range of temperature differences likely to be encountered (given a temperature coefficient of about 40μV $°C^{-1}$), when connected to the millivolt range of the CR21 loggers.

One junction of the reference pair was mounted in an aluminium block with a 100k thermistor (RS Components Ltd, Corby, stock number 151-243) similar to the Fenwal model UUT51J1 recommended by Campbell Scientific for use with the programme for temperature calculation included in the data loggers. This was done so as to allow the calculation of absolute temperatures within the profile.

To ensure good contact between thermocouples and air the junctions were held across the mouths of 5 cm diameter wire hoops, which were attached to the side arms of the mast holding the Vector anemometers. Although the thermocouple wire used was very fine indeed, tests showed that errors induced by the absorption of incident radiation were appreciable on bright days. Accordingly radiation shields were fitted. These were made from thin, white, plastic sheet wrapped around the hoops holding the

thermocouple junctions to form a tube about 5 cms long. The tubes were held approximately parallel to the wind to ensure good ventilation.

Linearity of amplifier circuits was checked with a precision voltage reference (Model 9535, Guildline Instruments, Smith Falls, Ontario, Canada).

Analysis of results

Results were analysed using the least squares method for calculation of profile parameters. As the available fetch was limited (and hence anemometers were quite close together) the data were analysed in a manner that would detect any errors in the data from

i) Anemometers interfering with one another through being too close together.

ii) Anemometers being held outside the log-linear zone of the boundary layer.

iii) Malfunction of instrumentation.

The minimum number of readings required for calculation of (d) with the least squares method is three. Hence each set of six readings was arranged into the twenty possible combinations of three readings. Values of the stability correction parameter were calculated for each half hour profile, and used in the calculation of values of (d), (z_o), and (u_*) for each of the twenty possible combinations. A worked example of stability correction

parameter calculation is given in appendix IV. Examination of calculated values of (d) then showed up any erroneous readings through consistently unlikely or impossible values of (d) (eg. values in excess of crop height). Any such readings were removed from analysis and profile parameters calculated using the remaining readings taken together. This procedure was carried out for each of the 20 or 30 profiles measured at each developmental stage for each variety. Finally, means, standard errors, and 95% confidence limits were calculated for each variety at each developmental stage, from the results calculated after the elimination of any dubious readings.

Measurements taken at times when the wind direction made large deviations from that prevailing at the time when the anemometers were set up (hence reducing the available fetch) were also rejected.

RESULTS AND DISCUSSION

Only a limited number of results are available from LEDA anemometers due to problems with anemometer alignment and to inferior connectors. Both problems were overcome, the first by strengthening the mast with a second main upright pole, 10 cms from the first with side-arms bolted to both, and the second by judicious repairs to the connectors. Due to these difficulties the results shown below for the

above canopy profiles only use data collected by the Vector anemometers. However, a comparison of the available results taken with the two types of sensor is made in appendix VI.

Stability conditions over measurement periods were lightly to moderately unstable for most of the season. Conditions are summarised in appendix V. For consistency the correction term from equations 3.4 to 3.6 was used throughout.

Above canopy profiles

Values of (d) for all three varieties throughout the season are presented in table 3.8 and, together with data on crop height at each set of measurements in figure 3.6. Similar trends in the ratio of (d) to crop height were evident for the conventional and semileafless crops where the highest ratios were found around mid-season, when plants were still flowering and starting to produce pods. The top of the canopy was at its most dense at this time due to the continued production of new leaf along with the flowers and pods. Later in the season internode length at the top of the canopy increased as leaf production stopped, reducing the canopy density in the upper layers despite growth of the pods. Such a trend was also possibly present in the leafless variety, though was masked by high ratios at growth stages 2 and 7.

Table 3.8 Variation in the zero plane displacement (d, m) (SE) for each variety through the 1984 season.

Growth stage	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
1	0.033	-	0.021
	(0.003)		(0.006)
2	0.057	0.080	0.049
	(0.004)	(0.004)	(0.003)
3	0.13	0.15	0.11
	(0.013)	(0.024)	(0.005)
4	0.25	0.26	0.26
	(0.024)	(0.012)	(0.015)
5	0.31	0.39	0.30
	(0.018)	(0.041)	(0.016)
6	0.42	0.42	0.38
	(0.012)	(0.029)	(0.017)
7	0.33	0.22	0.55
	(0.022)	(0.021)	(0.015)

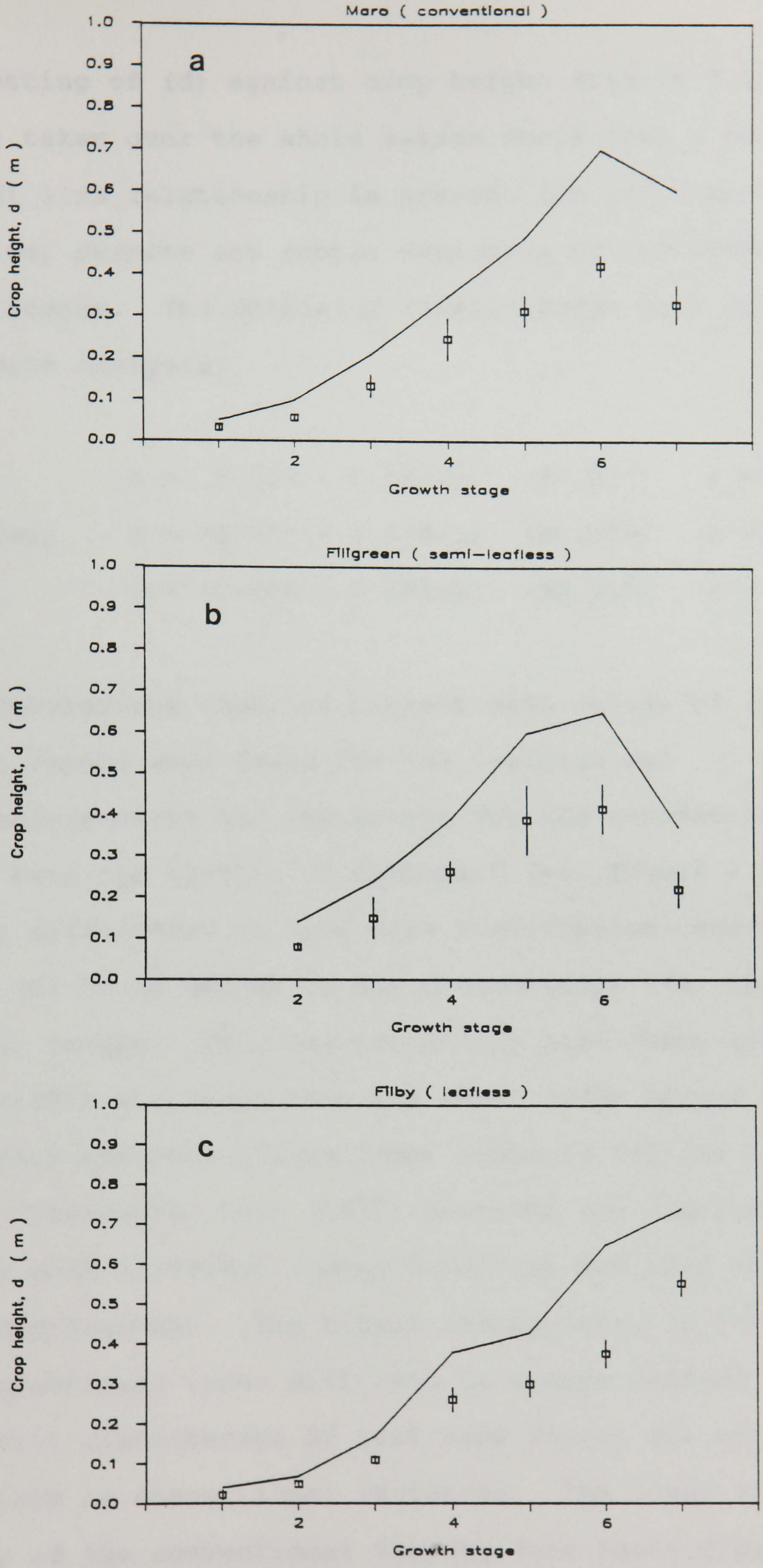


Figure 3.6 Variation of the zero plane displacement (d, □) with crop height (———) during the 1984 season for a) Maro, b) Filigreen, and c) Filby. Error bars show 95% confidence limits.

The plotting of (d) against crop height (figure 3.7) for results taken over the whole season shows that a very good straight line relationship is present for all three varieties, despite any subtle variation at different times in the season. The following relationships were found by regression analysis:

Maro;	d = 0.010 + 0.587(h)	(±0.037)	r = 0.990
Filigreen;	d = -0.010 + 0.660(h)	(±0.025)	r = 0.997
Filby;	d = -0.005 + 0.685(h)	(±0.055)	r = 0.984

It is interesting that the highest mean values of (d/h) for the season were found for the leafless and semileafless crops and the lowest for the conventional crop. From the results of chapter 2 (eg. figure 2.12, showing differences in leaf area distribution) one would expect (d) to be higher in the conventional (ie. the densest) canopy. This has previously been shown by Legg *et al* (1981) who found that the ratio (d/h) became greater for potato and bean (*Vicia faba*) crops as foliage area density increased. Thom (1971) mentions the complicating effects that different sowing densities may have upon zero plane displacement. The higher sowing rates of the non-conventional types will lead to a more uniform horizontal distribution of leaf area within the canopy in comparison to conventional varieties. The lower sowing density of the conventional variety (and hence greater distance between plants) allows deep penetration of gusts

Table 3.9 Variation of (d/h) for each variety through the 1984 season.

Growth stage	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
1	0.65	-	0.53
2	0.57	0.57	0.70
3	0.64	0.63	0.64
4	0.71	0.68	0.69
5	0.64	0.65	0.70
6	0.60	0.64	0.58
7	0.55	0.59	0.75

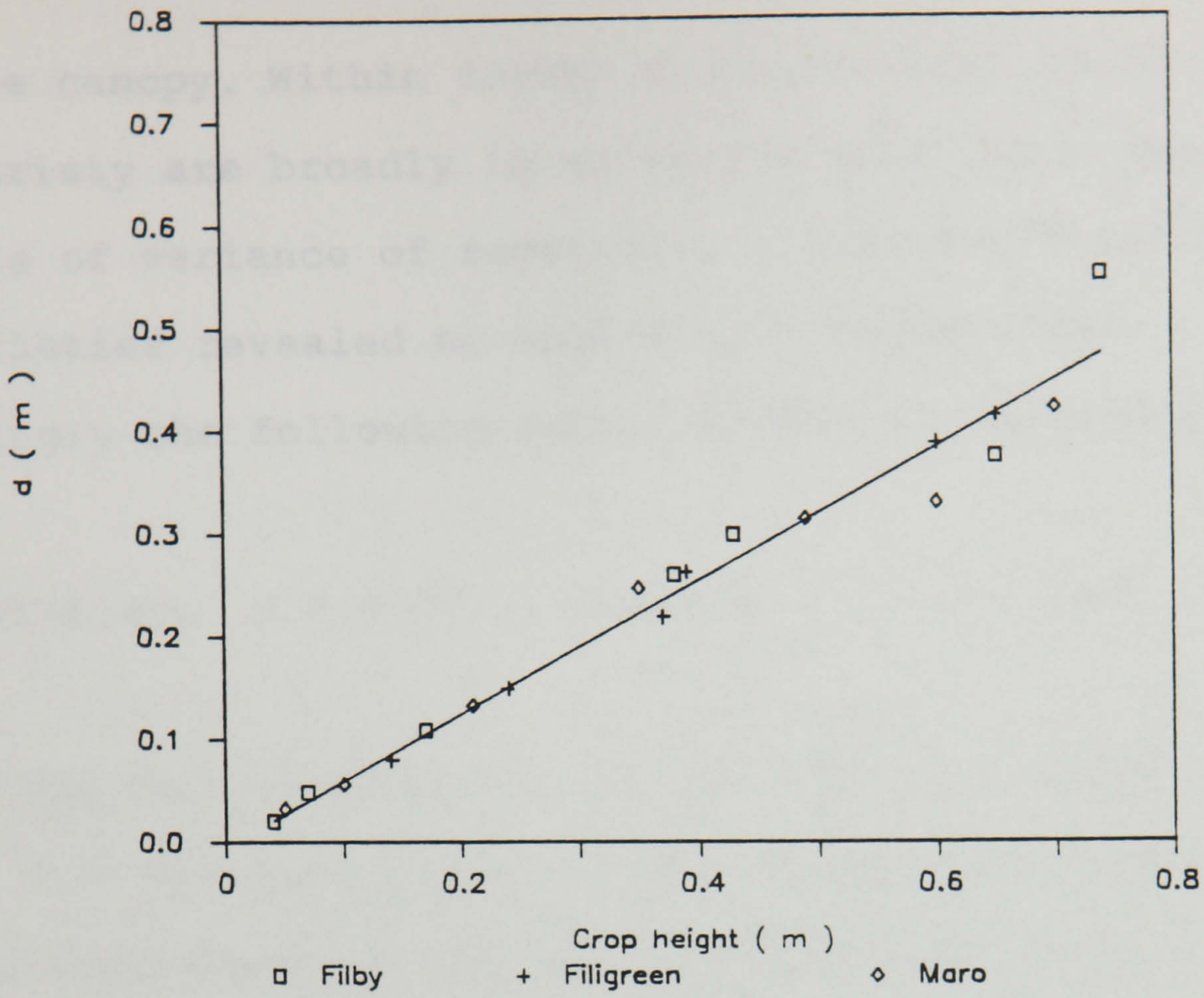


Figure 3.7 Zero plane displacement vs. crop height. No significant variation was found when comparing the regression coefficients of the three varieties, hence the slope shown is the regression of all values of (d) taken together, where

$$d = 0.644.h + 0.001$$

into the canopy. Within canopy profiles shown below for each variety are broadly in agreement with these results. Analysis of variance of regression coefficients between the varieties revealed no significant differences. Accordingly the following relationship was calculated:

All varieties; $d = 0.001 + 0.644(h)$ $r = 0.986$.

This slope for all cases of (d) vs. (h) is plotted in figure 3.7. The similarity of this equation with other general relationships for (d) and (h) is striking. Cowan (1968) gives the equation:

$$d = 0.64(h)$$

From measurements over a bean crop taken over a season, Legg *et al* (1981) found the relationship

$$d = 0.66(h).$$

The results shown here demonstrate that generalised relationships for (d) are useful for the pea crop even in cases where canopy structure differs markedly from normal. Such relationships are, however, not capable of detecting any subtle variation seen in (d) due to flowering or pod production.

Values of the roughness length (z_0) are presented in table 3.10 and figure 3.8. For most of the season values of (z_0) were lower for Filby than for Maro and Filigreen. A broadly similar pattern of variation over the season was found for all three varieties. Initially very low values of (z_0) were detected, remaining fairly steady until flowers appeared, despite growth of the crop. About halfway through the season (z_0) increased sharply, before decreasing gradually for Maro and Filby and remaining fairly constant for Filigreen. The increase in mid-season seems likely to be due to the combined influences of the appearance of pods and flowers and the increased height of the crop (relationships between (z_0) and crop height have been widely reported, see below). The subsequent decrease in (z_0) for Maro and Filby and levelling out of (z_0) in Filigreen as the crop dries out would, from this reasoning, appear surprising. However, the upper canopy becomes smoother as the production of new leaf stops, and leaves at the top of the canopy grow to the point where tendrils at this level connect up with one another, reducing the independence of these leaves to interact with the airflow.

Ratios of (z_0) against crop height (table 3.11) show much greater variation than the similar ratio with (d), and as a result no attempt has been made to produce relationships between (z_0) and (h) for the whole season. It seems likely that the higher values found at growth stage 1 (in Maro

Table 3.10 Variation of roughness length (z_o, m) (SE) for each variety during the 1984 season.

Growth stage	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
1	0.0034	-	0.0059
	(0.0004)		(0.003)
2	0.0034	0.0058	0.0027
	(0.0005)	(0.0007)	(0.002)
3	0.0077	0.0069	0.0053
	(0.0019)	(0.0007)	(0.002)
4	0.025	0.041	0.013
	(0.001)	(0.0049)	(0.007)
5	0.054	0.038	0.040
	(0.010)	(0.0044)	(0.019)
6	0.0427	0.0404	0.036
	(0.003)	(0.0069)	(0.005)
7	0.0358	0.055	0.027
	(0.004)	(0.009)	(0.0027)

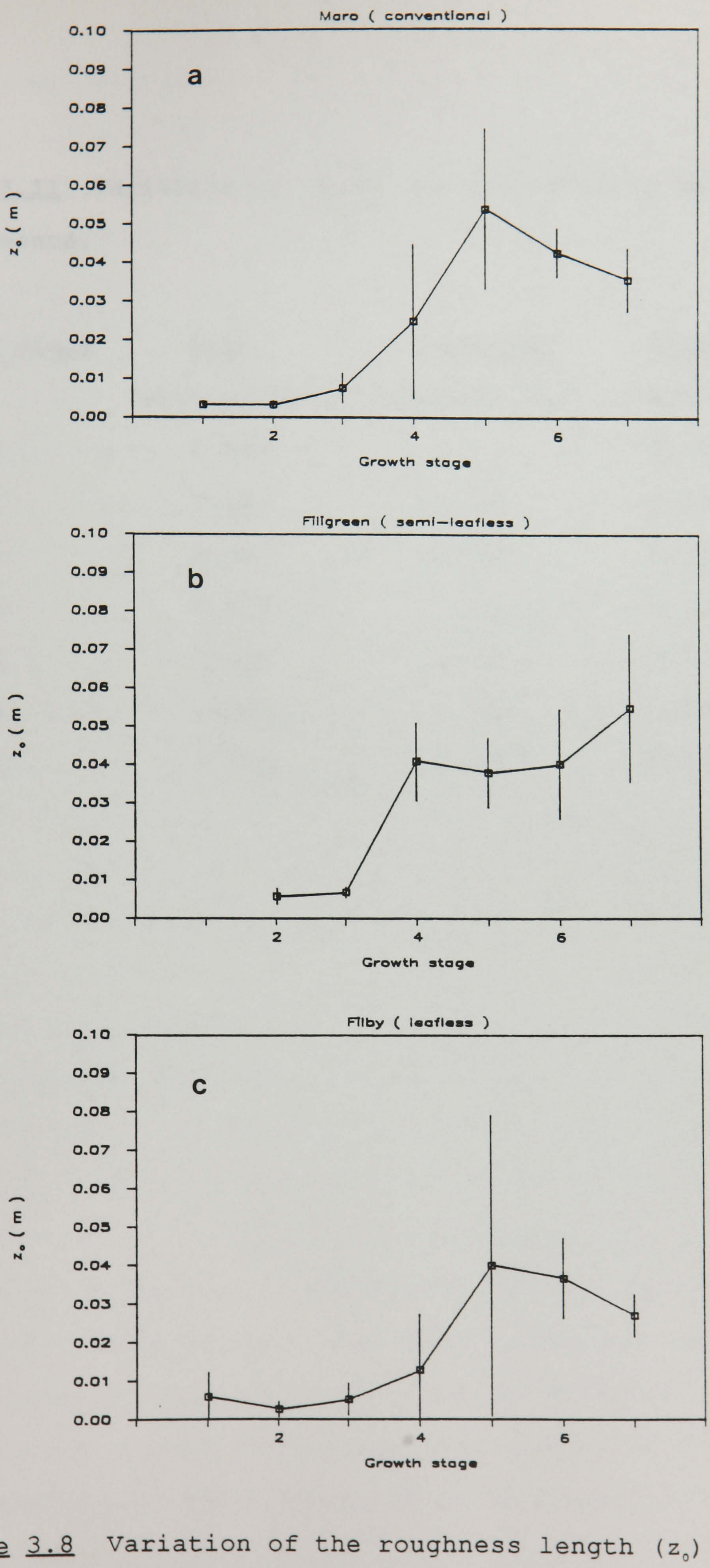


Figure 3.8 Variation of the roughness length (z_o) during the 1984 season for a) Maro, b) Filigreen, and c) Filby. Error bars show 95% confidence limits.

Table 3.11 Variation of (z_o/h) for each variety during the 1984 season.

Growth stage	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
1	0.068	-	0.148
2	0.034	0.041	0.039
3	0.037	0.029	0.031
4	0.072	0.105	0.034
5	0.092	0.064	0.093
6	0.061	0.062	0.055
7	0.060	0.149	0.036

and Filby) are due to a continued influence of the ground on the airflow, and the early state of development of the canopy. The full structure of the canopy had not yet developed (few, if any, tendrilled connections were present, due to both the spacing between plants and the small size of the early leaves and tendrils). It is clear that for most of the season (z_o) is poorly described by published relationships, eg. that given by Monteith (1973):

$$z_o = 0.13(h)$$

The results also disagree with the view given by Legg *et al* (1981) that the ratio (z_o/h) should decrease as canopy density (see figure 2.12) increases. This is another possible consequence of the differences in sowing density between the 3 varieties (see above).

No consistent trend of variation of either (d) or (z_o) with wind-speed was observed during the season for any variety. As discussed in the introduction to this chapter there is evidence on both sides to support the views that (d) and (z_o) are or are not dependent on wind-speed (see also Baldocchi *et al*, 1983, and Monteith, 1973). For modelling purposes it is preferable that both parameters are independent of wind-speed, to allow the accurate calculation of wind shear for a wide variety of wind-speeds. It seems likely that the rigidity of the pea

crop (before lodging) prevents changes in canopy structure which could lead to such variation as discussed by Monteith (1973) by way of explanation for the dependence found in rice crops and others. The plants within the canopy restrain one another from swaying to any great extent. Streamlining of leaves (other than a few newly developing at the top of the canopy) will be limited as they are held in position by their attachment to other plants by the tendrils. Only a very minor lowering of the canopy is observed due to strong gusts acting on the crop. Any effect of this is obscured by scatter around the mean of the parameters. The inflexibility of plants in a pea crop is probably disadvantageous as other plants, due to their flexibility, can streamline themselves and thus significantly reduce the drag acting upon them (see Monteith, 1973; Grant, 1985). It should be noted, however, that the range of wind-speeds over which measurements were taken for any set of readings was not great. Hence systematic variation of either parameter with wind-speed cannot definitely be ruled out solely on the basis of these results, especially, perhaps, when considering the problems of calculation of profile parameters to any great degree of precision (see appendix III).

On the assumption of no variation of (d) and (z_0) with wind-speed, normalised values of the shearing stress were calculated using equations 3.1 and equation 3.7(a). These

are presented in figure 3.9. Worked examples showing the method of calculation of both shearing stress and bulk canopy drag coefficient (below) are given in appendix IV. For most of the season momentum absorption was least in the leafless variety, whilst no consistent differences were found between the conventional and semileafless varieties. Probably the most similar study to date has been that of Baldocchi *et al* (1983, 1985) using normal and narrow leaved varieties of soybean. In that study, shortly before full cover, friction velocity was slightly higher over the narrow leaved variety. However, after full cover, friction velocities over the normal variety were higher by 25% (corresponding to a 40% greater shearing stress). This was attributed to increased bluff body effects due to the greater canopy density of the normal crop. For the period immediately before lodging in the pea crop (growth stage 6) differences in the normalised shearing stress between the conventional and semileafless varieties were minimal, though both exceeded the value for the leafless variety by about 11%. The lack of a difference between Maro and Filigreen appears to be a further consequence of the higher sowing density used for non-conventional types.

Values of the bulk canopy drag coefficient, (C_D), referenced to the level (d + 1) metres and calculated from equation 3.9, are given in table 3.12. As the canopies developed (C_D) increased to a maximum around mid-season.

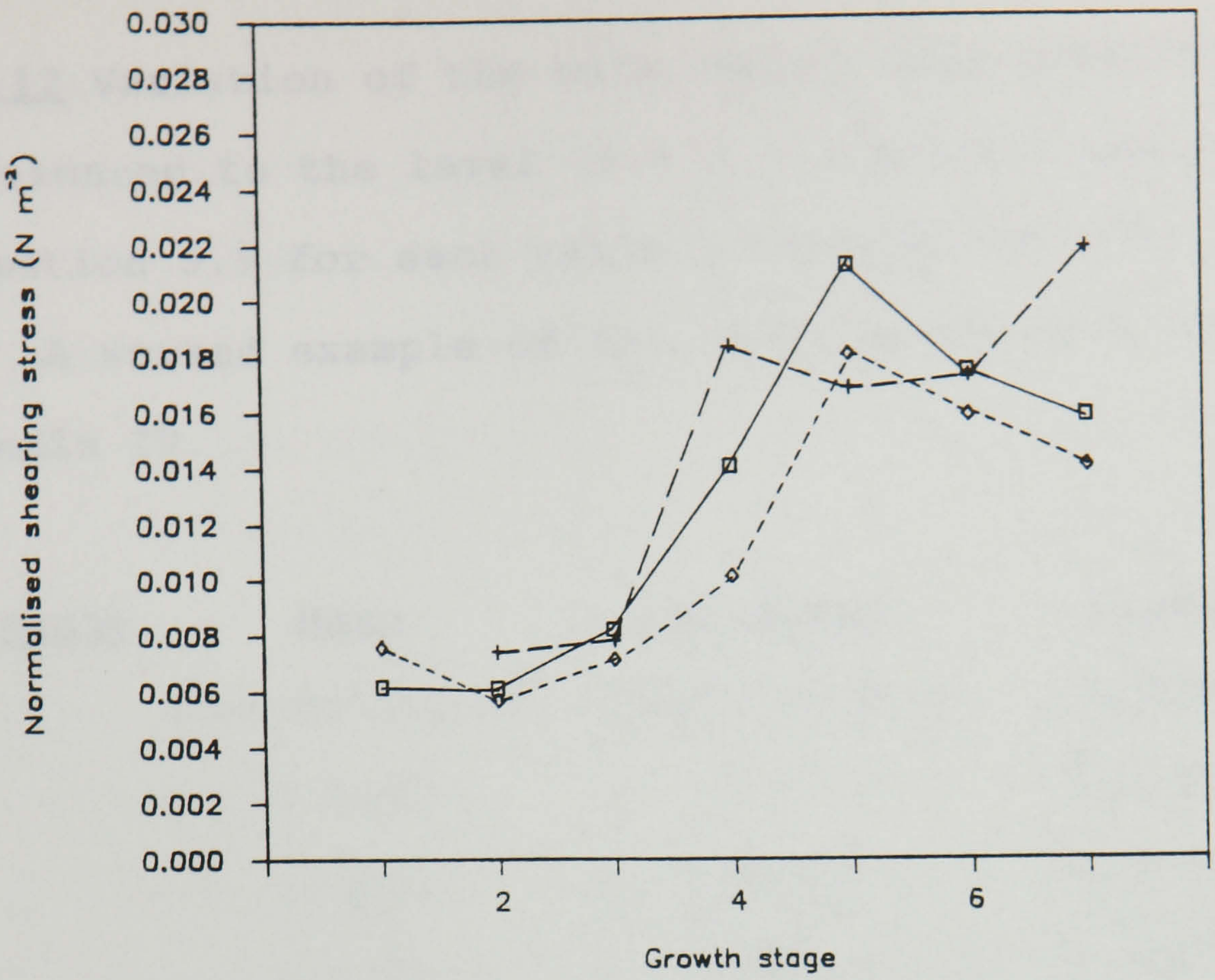


Figure 3.9 Normalised values of the shearing stress (τ) during the 1984 season for a) Maro (—□—), b) Filigreen (—+—) and c) Filby (--◇--). On the assumption that (d) and (z_0) do not vary with wind-speed, (τ) is calculated for all points with wind-speed at the height (h + 1) metres equal to 1 m s^{-1} and the density of air equal to 1.2 kg m^{-3}. A worked example is given in appendix IV.

Table 3.12 Variation of the bulk canopy drag coefficient (C_D) referenced to the level (z = d + 1 metres) calculated from equation 3.9 for each variety through the 1984 season. A worked example of the calculation of C_D is given in appendix IV.

Growth stage	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
1	0.0052	-	0.0064
2	0.0052	0.0063	0.0048
3	0.0071	0.0068	0.0061
4	0.0124	0.0165	0.0089
5	0.0197	0.0157	0.0162
6	0.0169	0.0163	0.0152
7	0.0152	0.0200	0.0129

Given the dependence of (z_o) on height (see above), and the dependence of (C_D) on (z_o) it is not surprising that (C_D) increased as the crops grew. Although comparison with results given for other crops is difficult due to differences in the height that (C_D) is referenced to and the range of developmental stages for which profiles were measured in this study, it seems safe to say that the values found here are lower than those found for other crops. For example in the case of soybean canopies Baldocchi *et al* (1983) give values of between 0.027 and 0.035, and Perrier *et al* (1972) give a value of 0.020. For beans Thom (1971) gives a range of 0.035 to 0.055 and Legg *et al* (1981) give a value of 0.022. Accordingly it seems that pea crops are less efficient in extracting momentum from the wind than crops of other species.

During the measurement of profiles during both the 1983 season (for which results are not presented), and the 1984 season, the phenomenon of 'honami' (the very pronounced waving of plants subjected to an airstream of particular turbulence characteristics, see Inoue, 1955) was not observed. This was probably due to the high level of coupling between plants (see chapter 2). The firm inter-plant connections in a pea crop prevent large scale movement, such as that which occurs in 'honami'. It would appear that absorbed momentum is dissipated in pea crops through flexing of the petioles, an effect which cushions the main stems from the full force of the wind. The

implication of this for canopy collapse in pea crops is that the role of wind may be much reduced in comparison to other species.

Martin and Juniper (1970) remark that pea leaves with damaged cuticular surfaces do not recover to the same extent as leaves of other species (eg. *Chrysanthemum segetum*, *Eucalyptus* spp.). Effects associated with such damage include altered stomatal behaviour, increased transpiration and increased sensitivity to herbicides (see Grace, 1977). It seems likely that the rigid manner in which pea leaves are held in a stand prevents them from flapping around, reducing the amount of damage that would otherwise be done to them. If damage of this sort is ordinarily minimal, the ability to repair such damage may be a luxury that pea plants can afford to be without.

Within canopy profiles

Normalised within canopy profiles for each crop during the period when the canopy was drying (growth stage 6) are shown in figure 3.10. Of the published relationships (see above) a much better fit was obtained using equation 3.11 from Thom (1971) than the equations from Landsberg and James (1971), and Inoue (1963) and Cionco (1965). The values of (α) for the 3 varieties were found through a least squares analysis and are given in table 3.13.

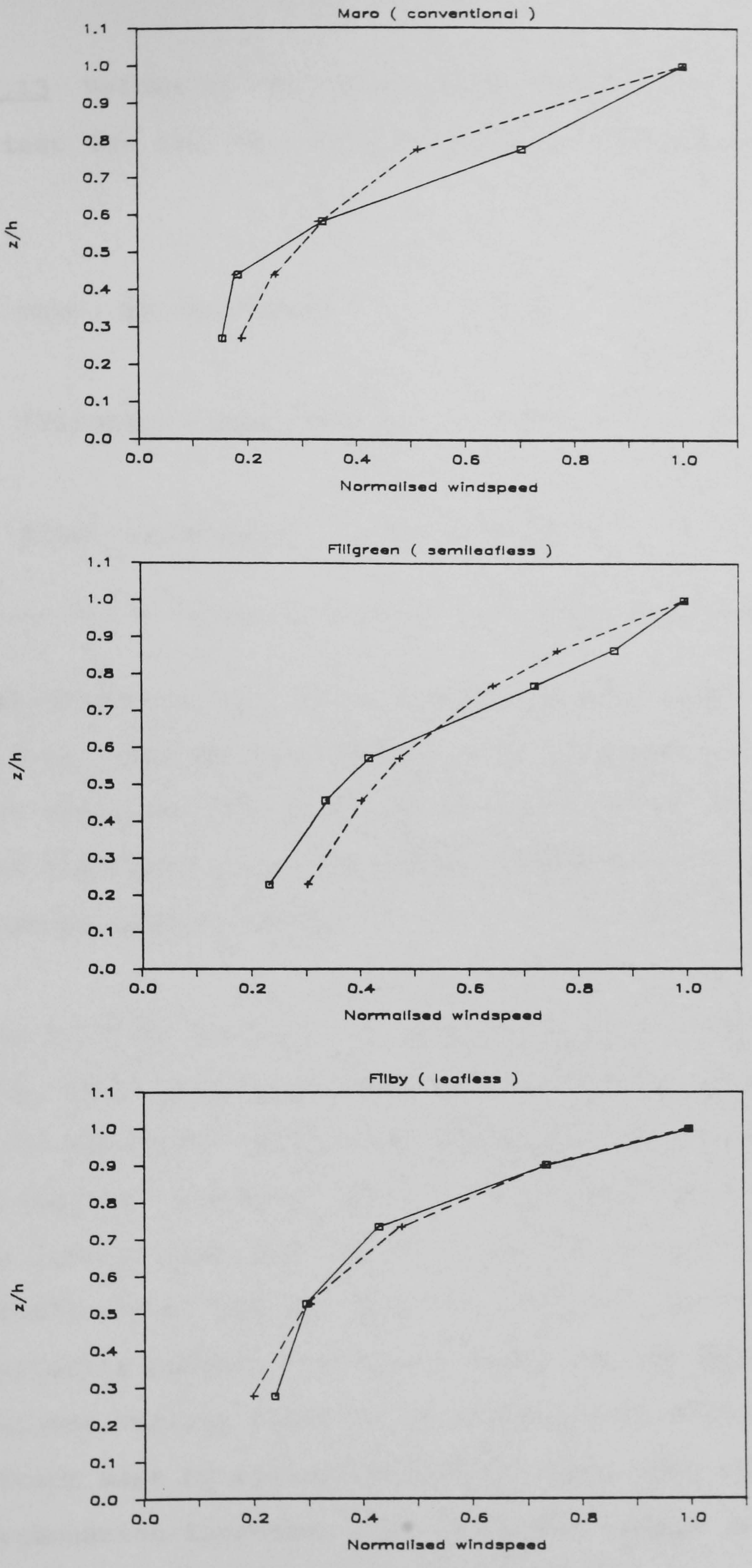


Figure 3.10 Normalised within canopy profiles (—□—) taken as the crop dried out for a) Maro, b) Filigreen, and c) Filby, with predicted profiles (—+—) from the relationship given by Thom (1971) (equation 3.11) with (α) = 1.77, 1.03, and 1.73 respectively.

Table 3.13 Values of the canopy flow attenuation coefficient (α) for the varieties Maro, Filigreen, and Filby.

Maro (conventional)	1.77
Filigreen (semileafless)	1.02
Filby (leafless)	1.73

Profiles predicted from these values are also shown in figure 3.10. Whilst this gives a very good fit for Filby, that for the other two varieties is not so good, wind shear in the upper canopy is overestimated and in the lower canopy underestimated.

As found by other workers (eg. Baldocchi *et al*, 1983, Legg and Long, 1975) wind-speed decayed most rapidly with height in the upper canopy, and thereafter more gradually. In the case of Filigreen, decay of wind-speed was seen to be more gradual than for the other two varieties, this being reflected by the low best-fit value of (α) found. The similarity between the conventional variety Maro and the leafless variety Filby is in disagreement with the observation made by Pereira and Shaw (1980) that canopy flow attenuation increases with increased canopy density. However, C. Jones (personal communication), taking within

canopy profiles for conventional, semileafless, and leafless crops at 2 densities found no differences between crops. As mentioned in the discussion of the lower ratio of (d/h) found for the conventional crop (see above) it would appear that the lower wind shear seen in comparison with the leafless variety was due to the lower sowing density of the conventional variety. It is surprising that there was not better agreement between the leafless and semileafless varieties, especially in view of the results from C. Jones (personal communication).

CONCLUSIONS

1. For all three varieties a good description of the variation of (d) through the season was given by

$$d = 0.644(h).$$

For most of the season values of (d/h) for the non-conventional varieties were higher than those for the conventional type. This was, at least in part, a consequence of the higher sowing rate used for leafless and semileafless varieties.

2. (z_0) was generally lowest for the leafless variety, with no clear difference between the conventional and semileafless varieties.

3. Shearing stresses at around the time when lodging occurred, were similar for the conventional and semileafless canopies and about 11% greater than for the leafless crop. The difference between Maro and Filby was fairly constant for almost the whole season (although the stress acting on Filby early in the season was higher, probably due to the continued influence of the soil surface upon the airflow). For the semileafless variety (τ) was greater than for the leafless for most of the season, though bore no consistent relationship to the pattern of variation found for the conventional genotype.

4. In comparison to trees, or plants in cereal crops, pea plants do not sway very much under the action of even fairly strong winds. This is a result of the extent of the inter-plant connections within a pea canopy, which cushion the main stems from the full force of the wind. This has implications for the importance of the role of wind in comparison to the other forces present in canopy collapse in dried pea crops, and also for the mechanism by which it occurs.

5. Within canopy profiles showed momentum absorption in the upper canopy to be greatest for the leafless variety. This was not expected from prior consideration of the differences in crop area density between the three varieties. It seems likely that differences in sowing density account for this result in part, though the

differences in leaf morphology could also be involved. For all three varieties the profiles were best described by the relationship proposed by Thom (1971), though for Maro and Filigreen momentum absorption in the upper canopy was overestimated, and in the lower canopy underestimated. This relationship, however, described within canopy wind-speed variation for Filby very well at all levels.

CHAPTER 4

WIND-TUNNEL MEASUREMENTS OF DRAG ON ISOLATED LEAVES AND PODS

INTRODUCTION

Some of the results in chapter 3 (above) appear to contradict results and observations made by other workers. For example, comparison of the ratio of zero plane displacement to canopy height (d/h) between the three phenotypes showed higher ratios for the leafless and semileafless crops than for the conventional crop. This result disagrees with the findings of Legg *et al* (1981) for bean (*Vicia faba*) and potato crops in which (d/h) increased over the season as canopy density increased. It seems likely that the observed differences are due, at least in part, to the different planting densities used for the three varieties. Another factor that must be considered is the extent of the morphological differences between the conventional, semileafless, and leafless varieties. Given that the physical attributes of leaves and other canopy components influence the transfer of momentum and other entities to the canopy as a whole (Monteith, 1963), it is only to be expected that alterations to leaf structure will have an effect on momentum absorption. The work described in this chapter

was, therefore, performed to improve understanding of the momentum absorption characteristics of pea plants differing in leaf morphology.

Measurements of the drag exerted on plants or parts of plants held in a wind-tunnel have been reported for beans (*Vicia faba*, Thom, 1968), and several species of conifer (Raymer, 1962; Mayhead, 1973; Grant, 1985). Drag has been found to be dependent both on wind-speed and on the angle between leaf (or shoot) and air flow (Thom, 1968). Values of the drag coefficient (C_d) for individual canopy elements can be calculated from equation 1.4 written (following the convention observed in meteorology, see Thom, 1975) in the form:

$$F = \rho.u^2.C_d.A \qquad 4.1$$

where F = force acting on sample at a wind-speed (u)
A = area of sample.
ρ = density of air

The area of a sample can be defined as projected area, area shown directly to the air stream, or total surface area. The value of (C_d) is obviously dependent upon the definition used. In this study projected leaf area was used throughout as it is the easiest to measure, follows the convention of Thom (1968) and allows shelter factors (see below) to be calculated from the results of projected leaf and pod areas given in chapter 2.

Assuming that the angle of incidence between leaf plane and air flow is constant and that there is no transfer of horizontal momentum to the soil surface, the total drag (f) acting on a canopy can, at least in theory, be described by

$$f = \rho \int_0^h u(z)^2 . \sum [A_j(z) . C_{dj}\{u(z)\}] . dz \qquad 4.2$$

where $A_j(z)$ = projected area of canopy element (in this study leaves or pods) type (j) at height (z)
$C_d\{u(z)\}$ = drag coefficient of canopy element type (j) at the wind-speed u(z).

By expressing projected areas as the area index for each canopy element type, (f) becomes the force per unit ground area, and hence may be equated with the shearing stress, (τ). Thom (1971) showed that this relationship, using theoretically calculated values for individual crop elements, described momentum absorption very well for a model canopy made from rigid cylinders 1 mm in diameter at a density of 1 cm^{-2}. However, for a more complicated bean canopy Thom (1971) found it necessary to introduce a shelter factor (p_d), such that

$$f = p_d . \tau \qquad 4.3$$

For a bean crop Thom gives a value for (p_d) of 3.5, though this was heavily dependent on the angle between leaf plane and the air flow. Out of necessity (p_d) is assumed to be constant throughout the canopy. From the result found for the model canopy (where $p_d = 1$) Thom reasoned that cases where (p_d) is greater than 1 arise not as a result of the

turbulent shear flow present in and above a crop (experienced both by his model canopy and the bean crop), but due to the complex and dense nature of a plant canopy. Further evidence for this view comes from Landsberg and Thom (1971) studying spruce shoots, and Landsberg and Powell (1973) studying apple seedlings, who both showed that transfer rates per unit leaf area decrease as density of needles on shoots, or leaves on twigs, increases.

MATERIALS

As in previous chapters the following cultivars from the near isogenic series MISOG1 (by John Innes Accession number) were used:

JI1194 (conventional)

JI1195 (semileafless)

JI1198 (leafless)

Twenty plants of each variety were grown in the soil mix U.C. II D (Baker, 1969) in a greenhouse at 15°C (minimum) with a daylength of 16 hours. Canes were used to support growing plants. Measurements were made when pods had just filled out.

METHODS

Design of the drag sensor

Two sensors were made, both based on more or less the same design: force exerted on a sample is transmitted down a probe to a sensing plate on which were mounted two or more strain gauges. Deformation of the plate alters the resistance of the gauges, due to a lengthening or shortening of their conductive paths. This is sensed by incorporating the gauges into a Wheatstone bridge (see Sears and Zemansky, 1963, or any similar textbook), and monitoring the output.

Much care needs to be taken to negate the temperature sensitivity of strain gauges, as with many other resistive sensors. A number of methods to reduce such errors have been developed including self temperature compensation (where gauges are dedicated for use on materials with similar thermal expansion coefficients) and the inclusion of dummy gauges (attached to an unstressed sample of the material under examination, and held in an identical thermal environment) into the Wheatstone bridge. It is also necessary to ensure that gauges are properly glued down, as even very small air bubbles trapped between gauge and specimen will affect readings. Adhesives must be tested before use, not only to ensure that a specific glue is suitable for the job, but also to ensure that the

adhesive has not come from a defective batch of an otherwise suitable brand. These and other precautions are more fully discussed by Pople (1979).

The original (2 gauge) sensor is shown in figure 4.1. The body of the sensor was made from steel, shaped so as to give minimum disruption to the air flow. The sensing plate, made from mild steel, was fixed at one end and held vertically. Two small strain gauges (type CEA-06-062W-350, Welwyn Strain Measurement, Basingstoke, Hampshire), matched to the thermal expansion coefficient of the plate material, were glued to the plate using a pre-tested cyanoacrylate adhesive. Connections to the Wheatstone bridge for two gauges opposing one another are shown in figure 4.2.

A strain gauge amplifier (RS Components Ltd, Corby, stock number 308-815) was used on the bridge output. Output from the amplifier was monitored both by chart recorder and a digital volt meter with a logging facility. Bridge supply was monitored continually and held constant at 9V.

This sensor had a linear response to applied load and, from calculations based on the results given by Thom (1968), was sensitive enough to measure the forces acting on small parts of plants at low wind-speeds. The design, however, was not ideal. Loading samples onto the probe deformed the plate in the gauge plane (thus unbalancing

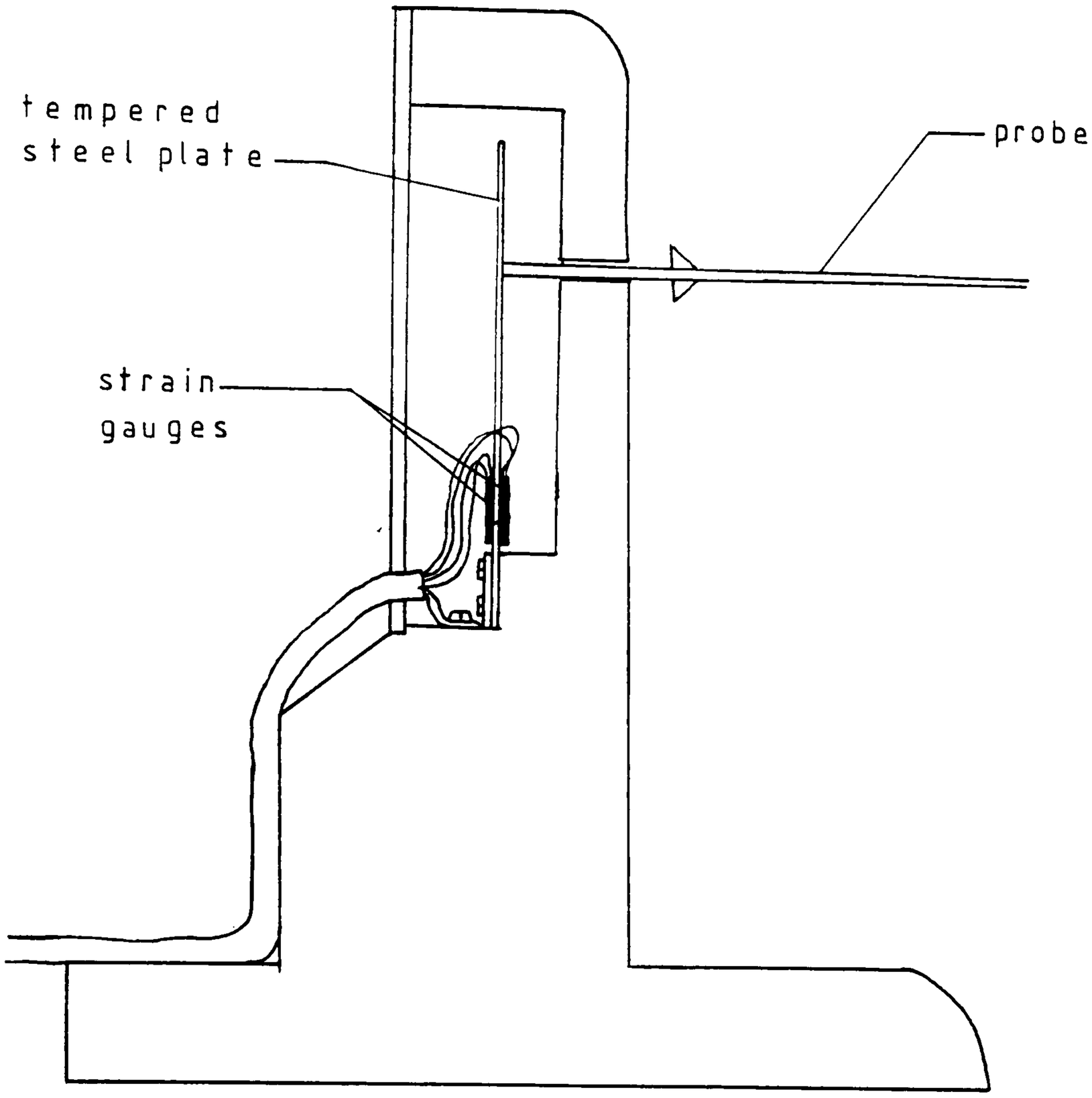


Figure 4.1 Design of the 2 gauge drag-force sensor, with tempered steel sensing plate held vertically and fixed at one end only. Although this design was sensitive enough to measure forces acting on individual leaves, problems were found that made it difficult to take accurate measurements.

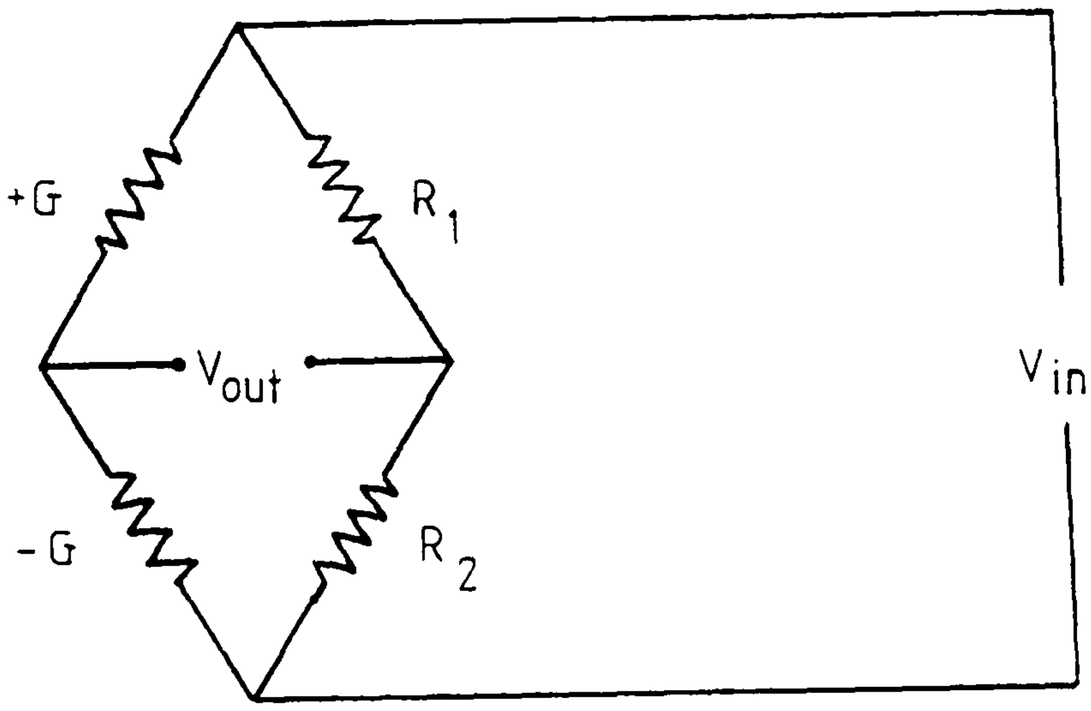


Figure 4.2 Connections to Wheatstone bridge for two gauges, one under tension (+G) and the other under compression (-G). The resistors R_1 and R_2 complete the bridge.

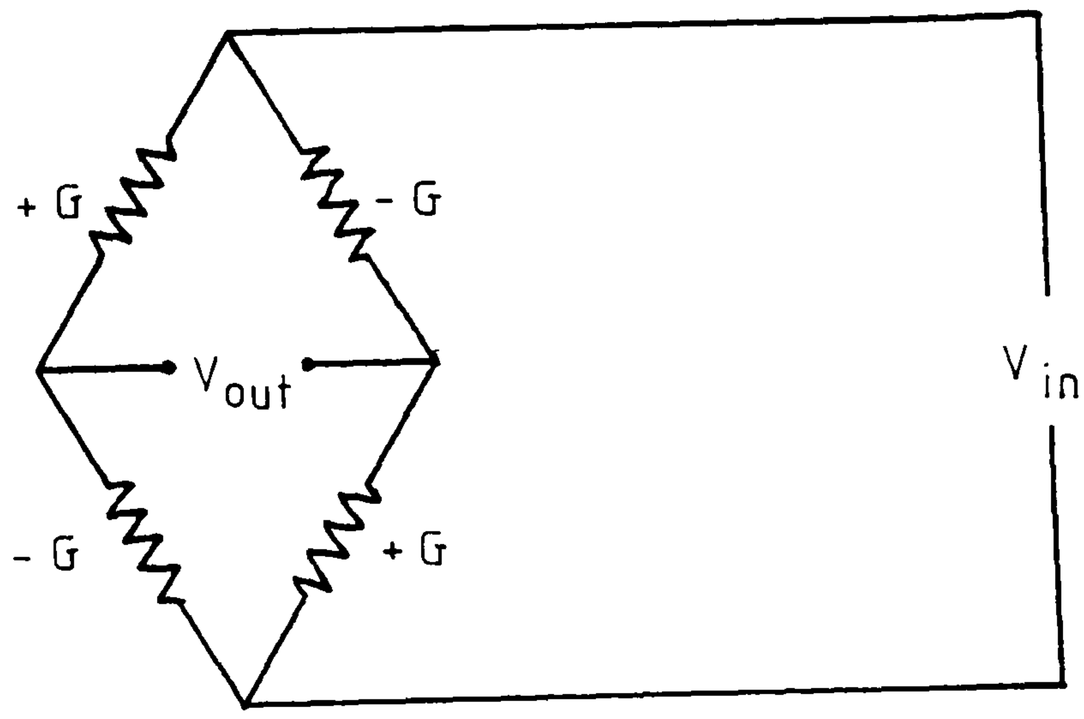


Figure 4.3 Connections to Wheatstone bridge for two pairs of gauges, one pair under tension (+G), and the other under compression (-G).

the bridge), and the sensor had to be zeroed for each new sample. Also oscillations of the plate, to which this design was prone, made it very difficult to take accurate readings.

The second design (the 4 gauge sensor, figure 4.4) eliminated these problems by mounting the sensing plate horizontally with both ends fixed to the super-structure. Loading of the probe in this design does not seriously unbalance the bridge as the principal axis of the gauges is perpendicular to the direction of the strain induced. Sensitivity of the system was increased by the use of four gauges rather than two, with one pair mounted at either end of the plate. Gauges were identical to those used in the first design. Connections to the Wheatstone bridge for a 4 gauge system are shown in figure 4.3 (above).

To make the instrument more versatile without having to use extra gauges, the sensing plate was made as a sandwich, with gauges attached to thin mild steel plates held on either side of a thicker central plate. Hence it is only necessary to replace the central plate to decrease or increase sensitivity (eg. for measurement of larger or smaller samples). Care must be taken, however, to ensure that the force acting on the plate is properly transmitted from the main plate to the gauges in such a design.

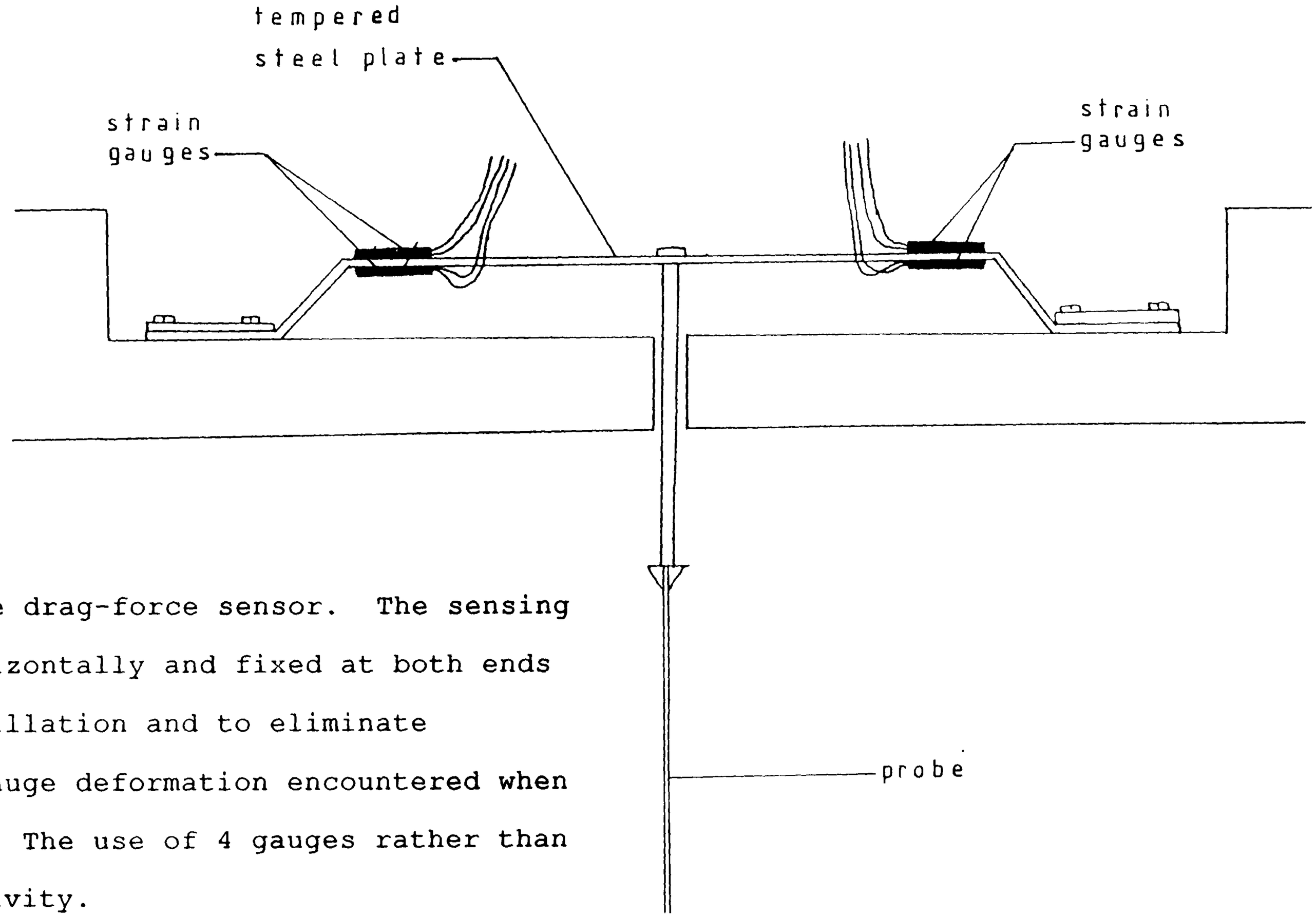


Figure 4.4 4 gauge drag-force sensor. The sensing plate was held horizontally and fixed at both ends both to reduce oscillation and to eliminate problems through gauge deformation encountered when loading the probe. The use of 4 gauges rather than 2 increases sensitivity.

Sensitivity may be altered by removing metal from the main plate in a position close to the gauges, which acts to focus the strain.

The instrument was calibrated using small precision weights. The calibration is shown in figure 4.5. A linear relationship between force and output was found over the full calibration range (0.0098 N to 0.98 N).

Wind-tunnel measurements

Samples were made up of a length of stem bearing 2 leaves. These were attached to the probe with stem held vertically and leaf axes at several angles relative to the air stream to account for the variation found in a crop.

Measurements were taken with leaves at angles of 90°, 45°, and 0° between flow and leaf axis (see figures 4.6 a, b, and c respectively) over a range of wind-speeds from 0.30 to 5.41 m s^{-1}. Pea leaves are arranged alternately up the stem. Hence the use of two leaves in each sample accounts for the two orientations individual leaves may have relative to the flow at the angles 0° and 45°: one with tendrils upwind of leaflets and the other with leaflets upwind of tendrils. For an angle of 90° both leaves present the same aspect to the wind.

Each leaf sample was used for a maximum of 5 minutes. Prior testing had shown that leaves used for periods

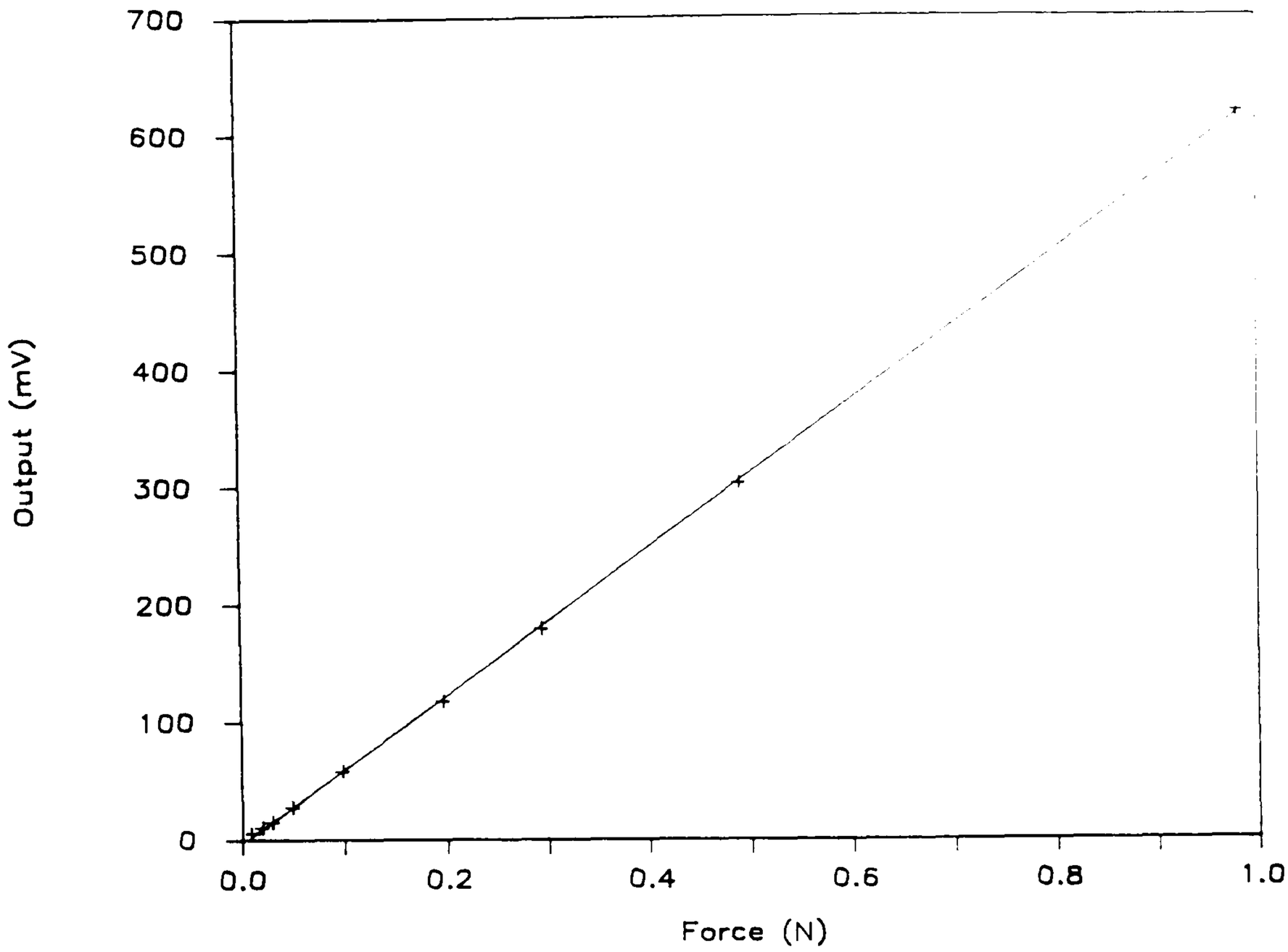


Figure 4.5 Calibration slope for the 4 gauge sensor, for the range 0.0098 N to 0.98 N. Output is seen to be linear over the entire range for which the sensor was calibrated.

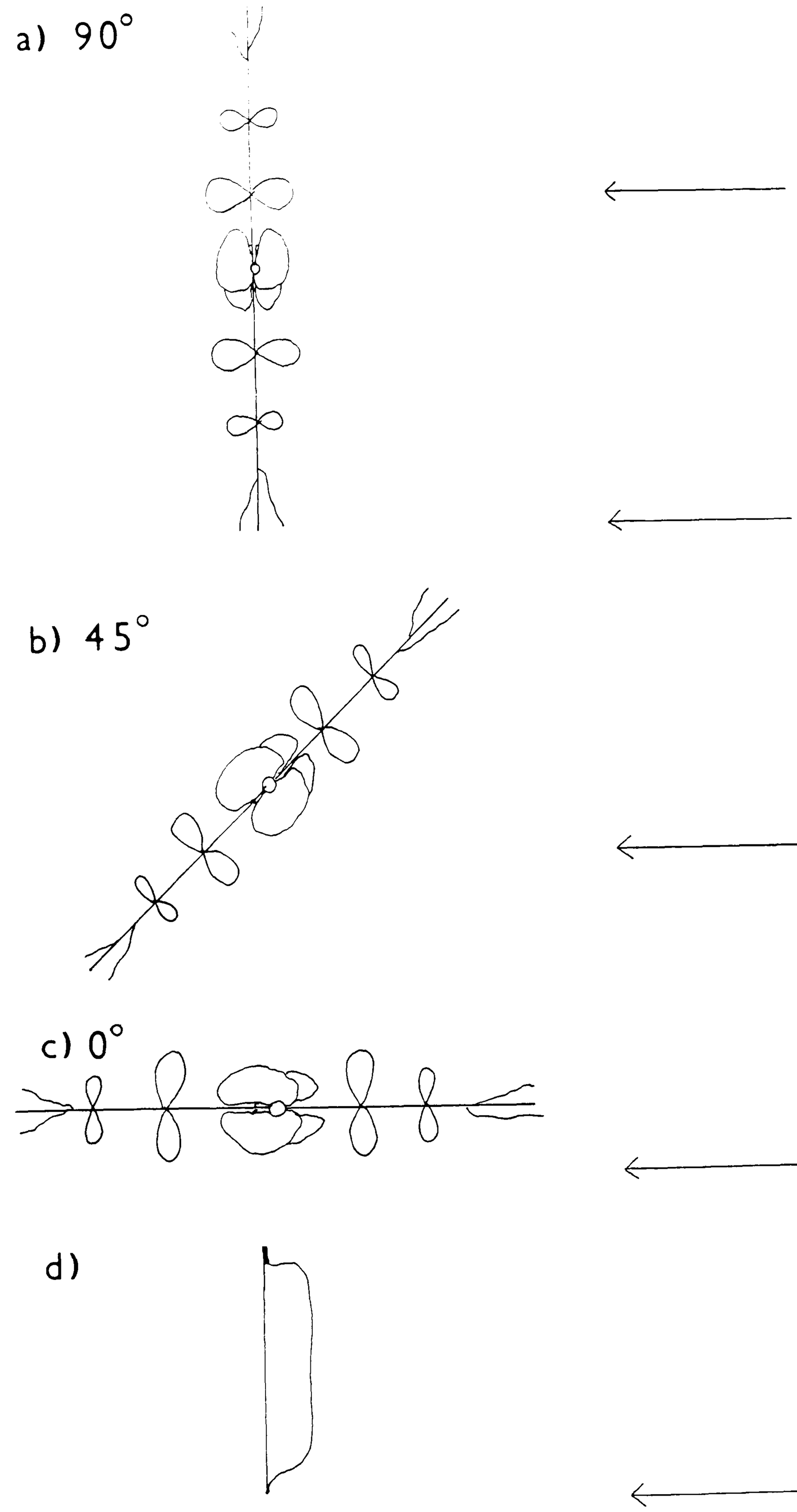


Figure 4.6 Definition of the angles a) 90°, b) 45°, and c) 0° between leaf axis and airflow, and d) position of pods relative to the airflow. Pairs of leaves are viewed from above and airflow is from right to left.

longer than this suffered reduced turgidity due to water loss. This allowed a maximum of only 4 or 5 measurements to be made with each leaf sample.

Pods were held side-on to the air flow for measurement (see figure 4.6 d). Unlike the leaves there was no problem with a reduction in turgidity, allowing a full set of readings to be taken on each pod.

At least four measurements were taken at each wind-speed and each angle for leaves and pods. Measurements were made in the wind-tunnel of the Department of Forestry and Natural Resources at the University of Edinburgh for wind-speeds between 1 and 5 m s^{-1}. For measurements at wind-speeds less than 1 m s^{-1} a fan was used. Wind-speeds in the tunnel were monitored with a heated thermistor anemometer (Model AVM 501, Prosser Scientific Instruments, Hadleigh, Suffolk), checked against a pitot static tube. Wind-speeds generated by the fan were measured with the heated thermistor anemometer alone. Leaf areas were measured using a Delta-T area meter (Delta-T Devices Ltd., Cambridge).

Drag coefficients for each leaf type, and pods, were calculated from equation 4.1. Shelter factors for the varieties Maro, Filigreen and Filby were calculated from equations 4.2 and 4.3, using the values of (C_d) found for each leaf type, leaf and pod areas from figure 2.12, and

the wind profile results of chapter 3. For each variety (τ) was calculated for the case where wind-speed at the height (d + 1) metres is equal to 5 m s^{-1}, using the mean values found for (d) and (z_o) just prior to lodging (based on the assumption that variation in (d) and (z_o) with wind-speed is negligible). Within canopy profiles were calculated from equation 3.11 using the best fit values found for (α) from the measurements taken with the vane anemometers in the field. This method for calculating shelter factors was checked and found to be correct using data and results from Thom (1970). Of the many quantities involved in the calculation of shelter factors most uncertainty is attached to the roughness length, (z_o) (see chapter 3). Accordingly errors associated with (z_o) were also calculated. A worked example of these calculations is given in appendix IV.

RESULTS

Drag coefficients for leaf samples from conventional, semileafless, and leafless plants are shown in figures 4.7, 4.8, and 4.9 respectively. Lowest values were found for samples from conventional plants, and the highest for samples from leafless plants. As was to be expected, values were greatest in all three phenotypes for samples held at an angle of 90° between leaf axis and air flow. Drag coefficients declined as wind-speed increased, and

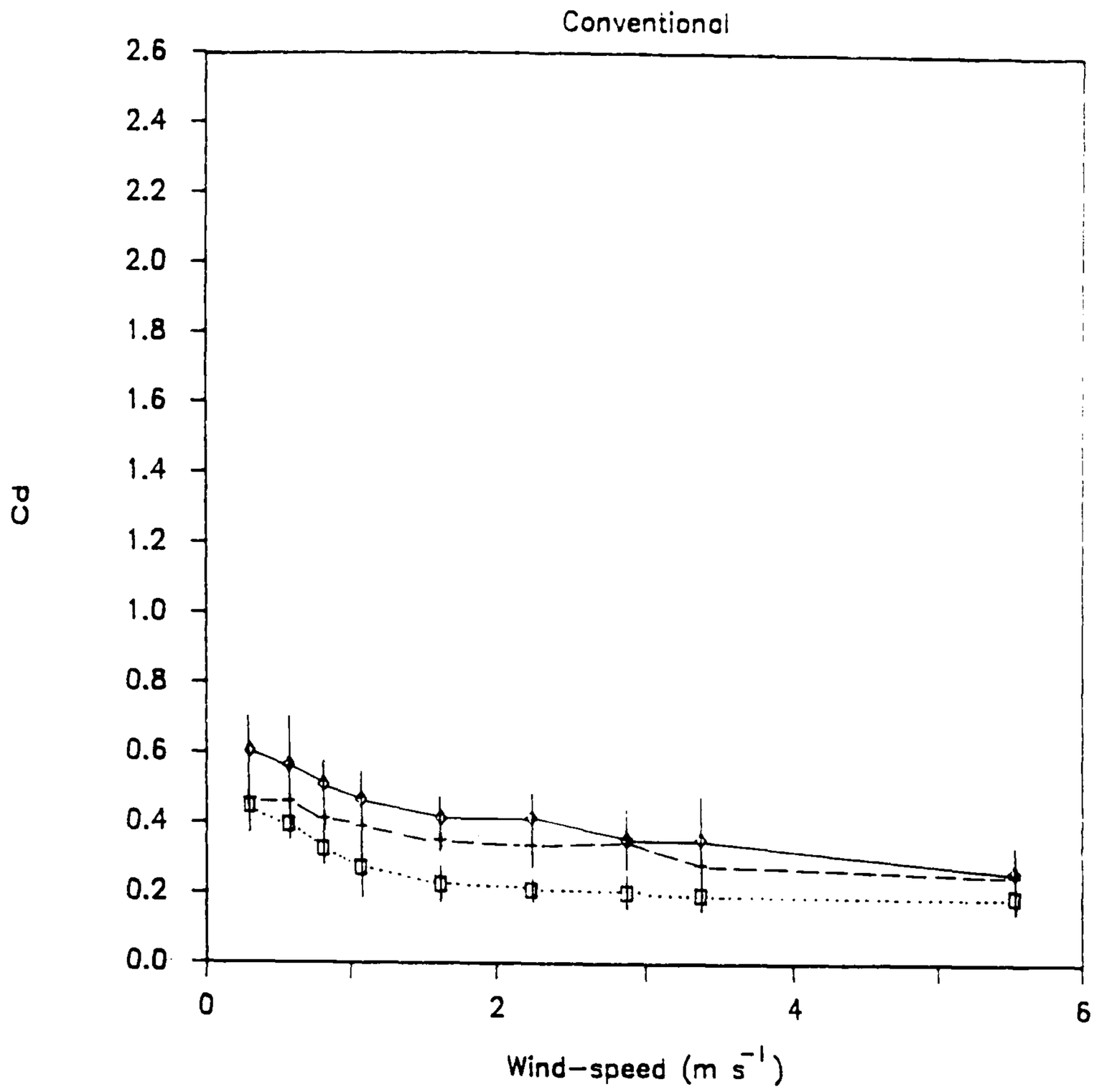


Figure 4.7 Variation of drag coefficient (C_d) with wind-speed at angles of 0° (·····□·····), 45° (– – ┼ – –), and 90° (——◇——), between airflow and leaf axis for leaf samples from conventionally leaved pea plants. Standard error bars are shown.

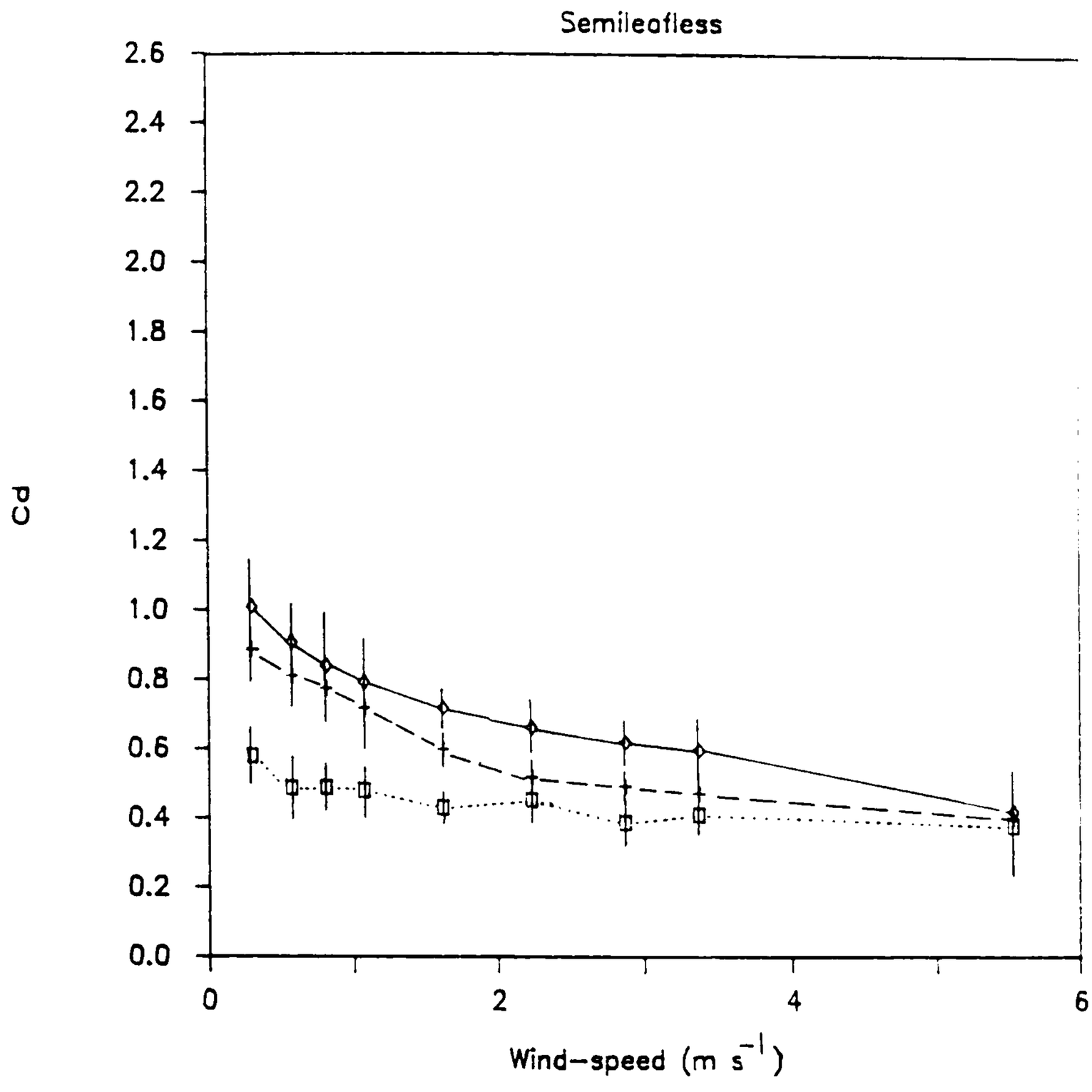


Figure 4.8 Variation of drag coefficient (C_d) with wind-speed at angles of 0° (·····□·····), 45° (– –+– –), and 90° (——◇——), between leaf axis and the airstream for leaf samples from semileafless plants. Standard error bars are shown.

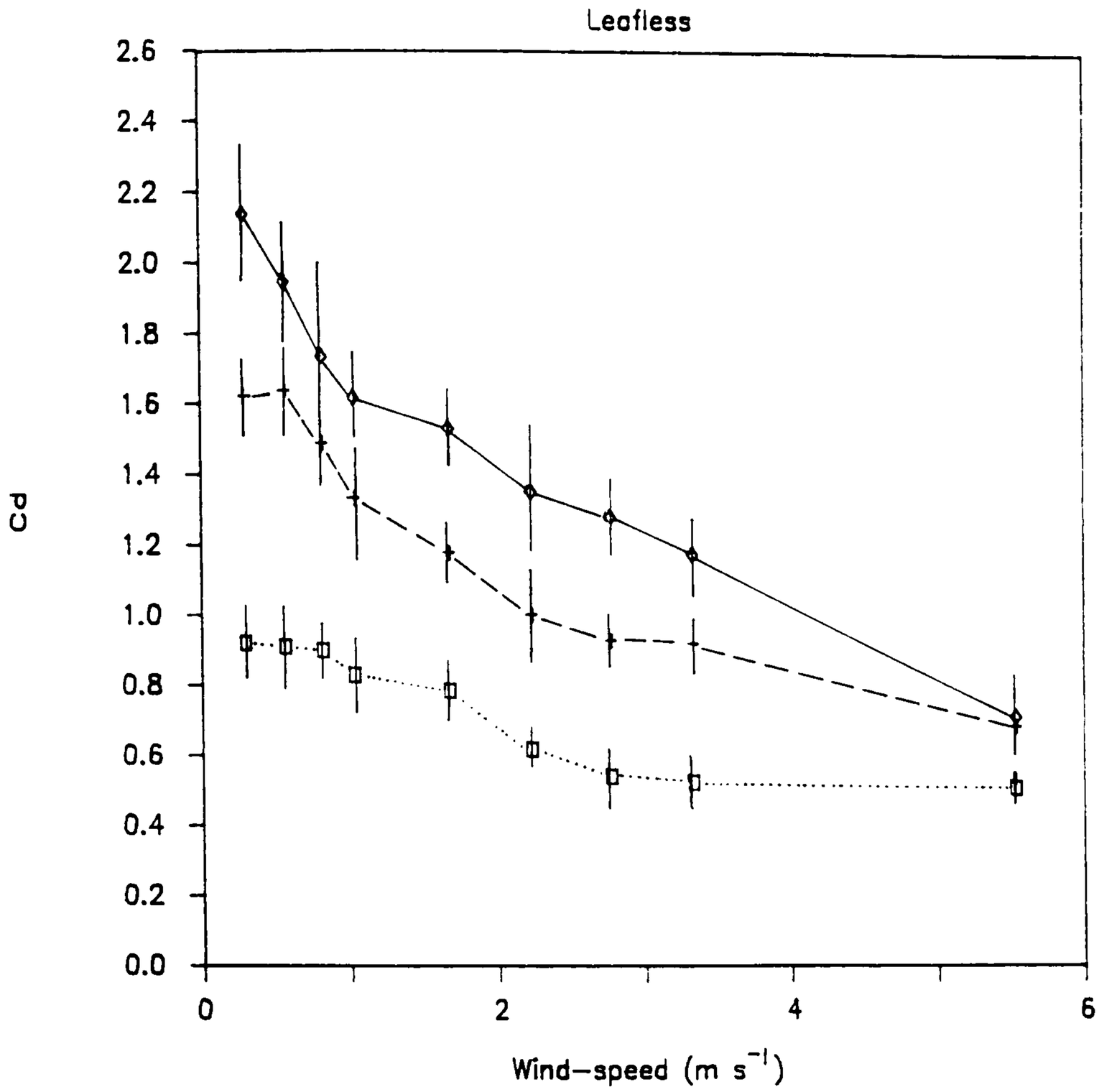


Figure 4.9 Variation of drag coefficient (C_d) with wind-speed at angles of 0° (·····□·····), 45° (– –+– –), and 90° (——◇——), between leaf axis and the airstream for leaf samples from leafless plants. Standard error bars are shown.

fell most rapidly in the range 0.30 to 1 m s^{-1}. Thereafter, (C_d) continued a more gentle decrease, probably due to streamlining, for samples from semileafless and conventional plants. For samples from leafless plants, however, (C_d) continued falling quite quickly. In all three phenotypes differences of (C_d) between the three angles decreased as wind-speed increased, this being most noticeable for the values recorded at the highest wind-speed used (5.41 m s^{-1}). Mean drag coefficients ($\overline{C}_d$), accounting for the variation in the angle between leaf axis and flow, have been calculated from the values of (C_d) for the three angles at each wind-speed used as:

$$\overline{C}_d = (C_d\{90°\}+C_d\{45°\}+C_d\{0°\}+C_d\{45°\})/4 \qquad 4.4$$

This expression accounts for the fact that if one rotates a pair of leaves through 360° the angles 0° and 90° are passed through once, whilst the angle of 45° is met twice.

Variation of ($\overline{C}_d$) with wind-speed for all three phenotypes is presented in figure 4.10. From equation 4.1 it can be seen that, at any wind-speed, the force per unit area leaf surface will be proportional to ($\overline{C}_d.u^2$). Variation of this quantity with wind-speed is shown in figure 4.11. The decay of ($\overline{C}_d$) as wind-speed increases is amply compensated for by the increased value of (u^2).

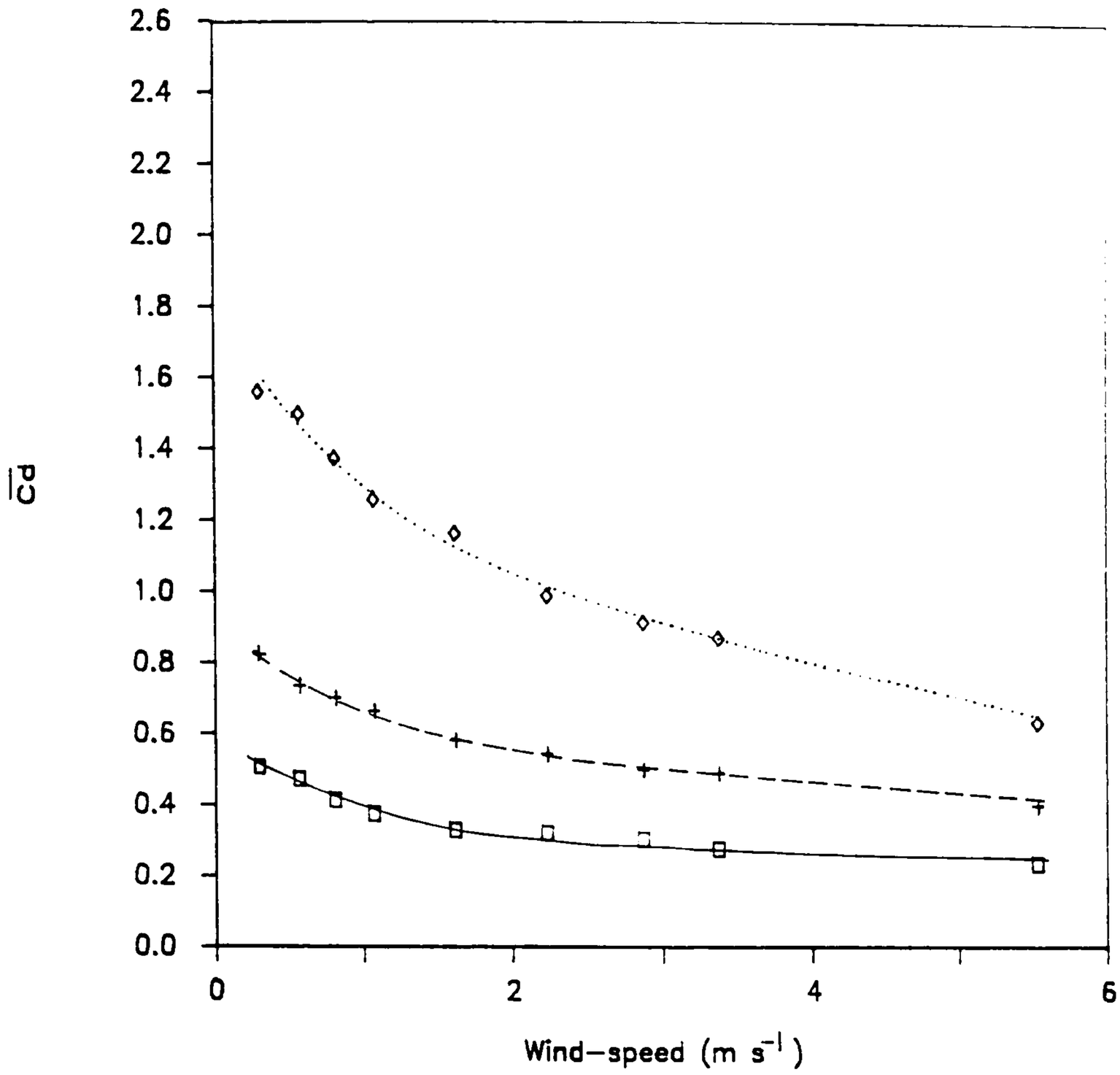


Figure 4.10 Variation of the mean drag coefficient ($\overline{C_d}$) with wind-speed for samples in a wind-tunnel, for conventional (·····□·····), semileafless (– – + – –), and leafless (—— ◇ ——) phenotypes. Curves were fitted by hand.

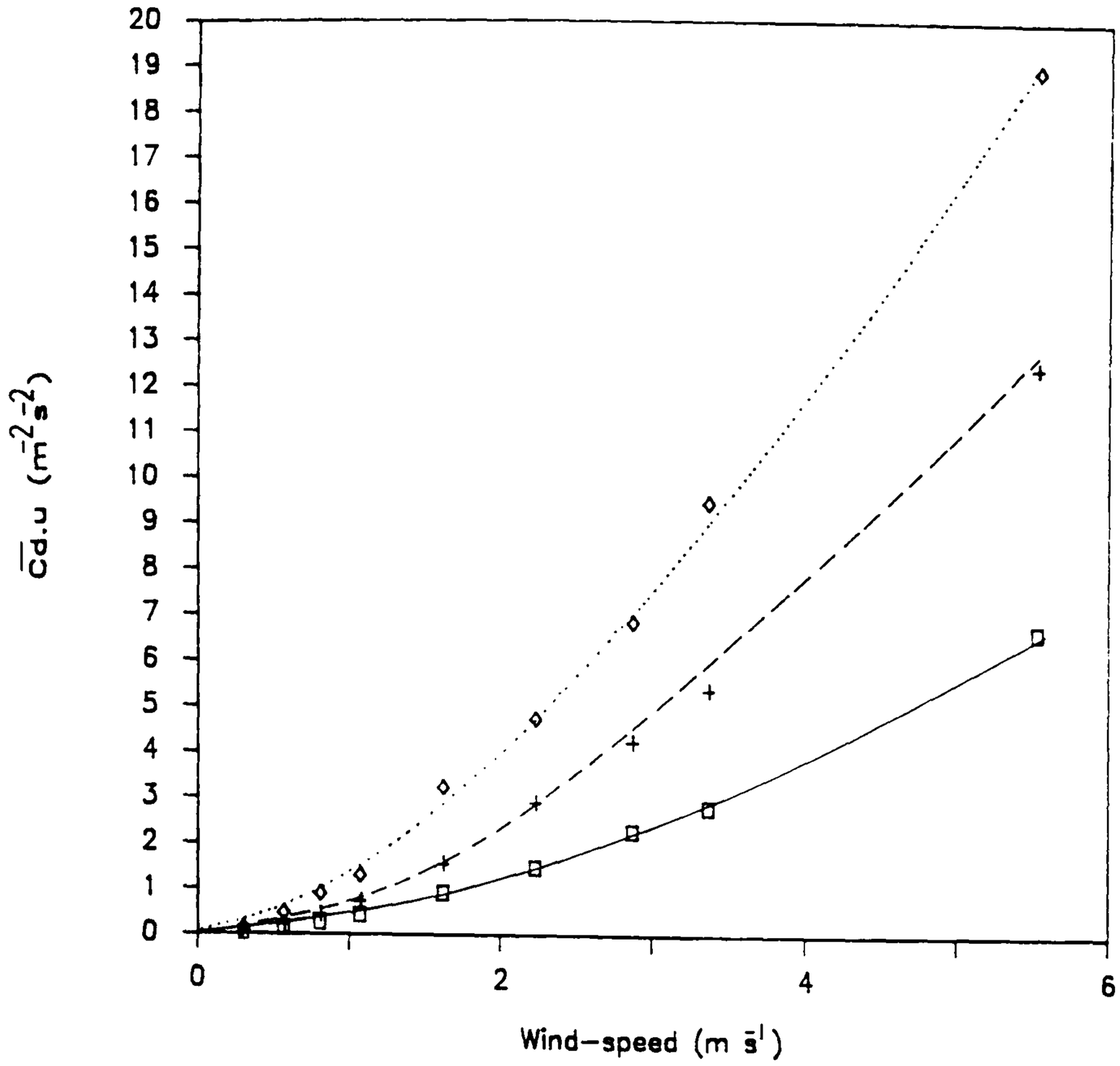


Figure 4.11 Variation of the quantity ($\overline{C_d}.u^2$) with wind-speed for samples in a wind-tunnel, for conventional (·····□·····), semileafless (– – + – –), and leafless (——◇——) phenotypes. Curves were fitted by hand.

Variation of (C_d) with wind-speed for pods is shown in figure 4.12. (C_d) decreased slightly for wind-speeds between 0.30 and 1 m s^{-1}. Unlike the leaf samples (C_d) remained fairly constant thereafter.

Calculated values of (p_d) (see worked example in appendix IV) for each phenotype are shown in table 4.1. Of the variables involved in the calculation of (p_d) most error is attached to the roughness length, (z_o). Accordingly, the errors shown in table 4.1 are those associated with the 95% confidence limits for (z_o) shown in chapter 3 (see appendix IV). Highest values of (p_d) were obtained for the leafless and semileafless crops, which were almost identical. It is clear that the error due to uncertainty connected with (z_o) can be large for calculations of this sort, stressing the importance of minimising errors when measuring wind profiles. It is quite possible that errors in other parameters will offset, at least partly, the error in (z_o). A better idea of the actual error in (p_d) would be gained using a more elaborate statistical analysis such as the log derivative method or by probable error analysis (see Fritschen and Gay, 1979). However in view of the wide disparity between shearing stress measured in the field and that calculated from the results in this chapter it does not seem worthwhile exploring the error in (p_d) in such depth.

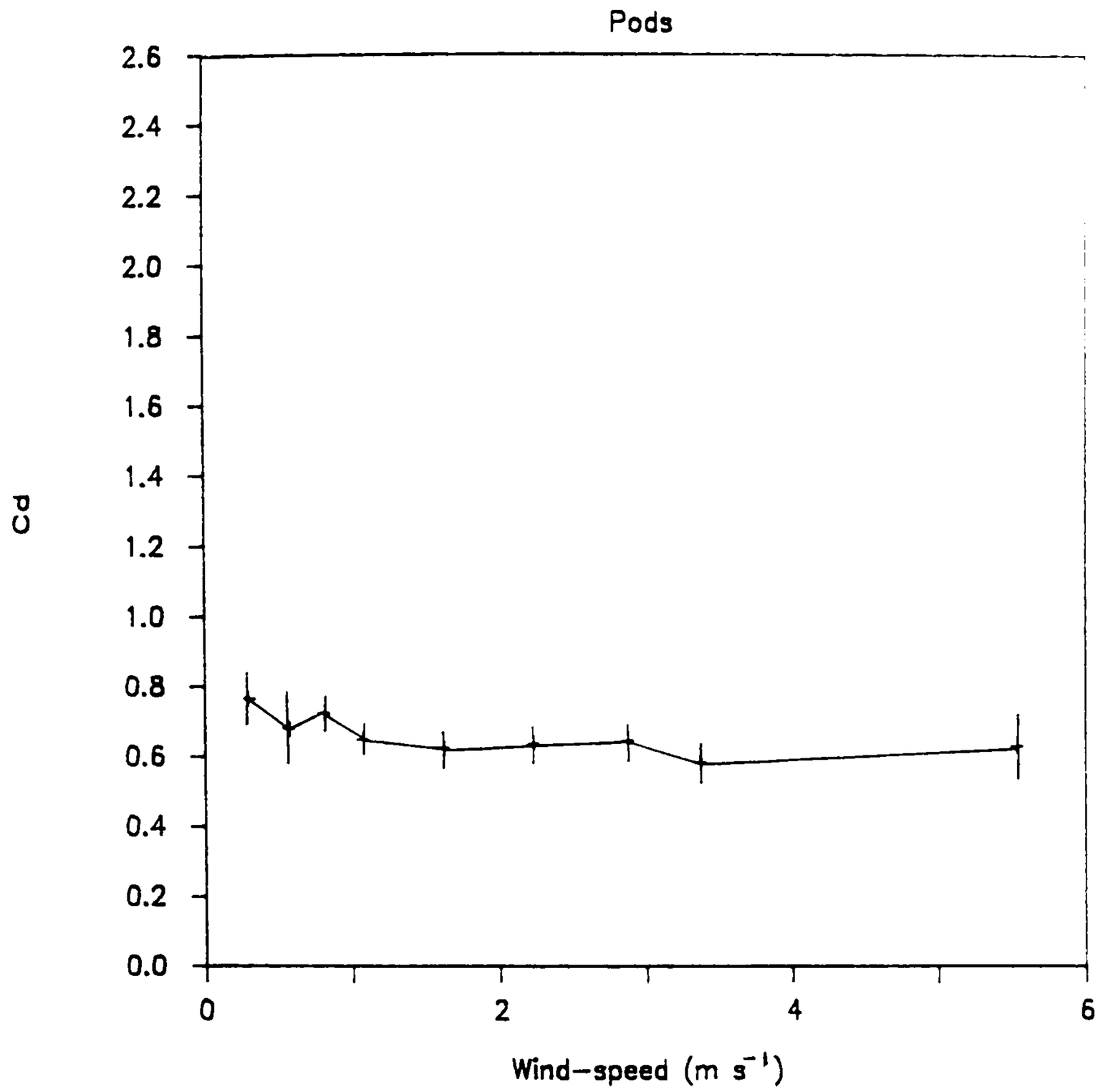


Figure 4.12 Variation of drag coefficient (C_d) with wind-speed for pods held side-on to the airflow. Standard error bars are shown.

Table 4.1 Shelter factors (p_d), with errors associated with the variability in (z_0), for pea plants of contrasting leaf morphology. Values have been calculated from equation 4.2 using measurements of drag coefficients of isolated canopy elements (see above), projected areas of canopy elements for crops in the field (see chapter 2), and above and within canopy wind profiles (see chapter 3), for the case where wind-speed at the height (d + 1) metres equals 5 m s^{-1}. Errors were calcuated similarly using the 95% confidence limits of (z_0) given in chapter 3 to illustate the effect of the uncertainty in (z_0) on the value of (p_d) obtained.

phenotype	p_d	error for z_0 + 95% CL	error for z_0 - 95% CL
conventional	8.07	-1.05	+1.29
semileafless	11.89	-3.42	+5.99
leafless	11.91	-2.75	+4.22

DISCUSSION

The values of (C_d) show that samples from plants of the leafless phenotype were more efficient in absorbing momentum on a unit leaf area basis in the wind-tunnel than leaves from semileafless and conventional cultivars. This is due to a number of factors. Drag coefficients for thin cylinders (eg. tendrils and petioles) are high in comparison to values for larger bodies (see, for example, Schlicting, 1968). Also to be considered are the differences in leaf architecture. Heath and Hebblethwaite (1985 c) have shown that the percentage of leaf made up of tendrils and petioles in mature plants of the three phenotypes studied here is approximately 10%, 25% and 80% for conventional, semileafless, and leafless varieties respectively. Leaves and stipules approximate to two dimensional structures, their length and width greatly exceeding their thickness. With leaves held at angles relative to the air flow typical of those to be found in a crop, the area of leaflets and stipules presented directly to the wind is thus only a fraction of the projected leaf area. Thom (1968) showed drag on leaves to be heavily influenced by variation of angle between leaf plane and wind. Isolated petioles and tendrils, however, are more or less cylindrical, and thus present a similar area to the wind no matter from what angle perpendicular to their axis the wind comes. At the end of a petiole, tendrils form into three dimensional bunches (see plates III and

IV). As air flow will be able to penetrate through these loose bunches each tendril should be fairly well exposed to the wind. Tendrils within bunches will shelter one another, but probably only to a very limited extent. Landsberg and Thom (1971) found shelter factors between needles on Sitka spruce shoots of about 1.4. Given the comparatively dense nature of a coniferous shoot one might expect a shelter factor even closer to 1 for the interaction between tendrils on a pea leaf.

The reduction in (C_d), as the angle between leaf axis and flow changed from 90° to 0°, was expected as the area presented directly to the wind at the lower angles is reduced for all three phenotypes.

Values for (C_d) derived theoretically or using rigid samples show a rapid decline of (C_d) between 0 and 1 m s^{-1}, and a fairly constant value thereafter (see Thom, 1971). In figures 4.7 to 4.10 (C_d) decreases most rapidly in the range 0 to 1 m s^{-1}, though continues to fall for higher wind-speeds, through streamlining (distortion of leaf structure due to the incident air flow). Raymer (1962) found a similar continued decline with increased wind-speed for trees held in a wind-tunnel. In a pea crop one would expect little streamlining even at higher wind-speeds (which would seldom, if ever, be found within a crop) due to the manner in which leaves hold firmly onto

anything they meet. In the light of the high shelter factors found, however, minor discrepancies such as those due to streamlining seem irrelevant.

The high values found for (p_d) demonstrate that the description of momentum transfer to the canopy as a whole, by the application of the measured drag coefficients, was poor. In all cases (p_d) is much greater than the value of 3.5 found in the most comparable study to date (Thom, 1968; 1971; 1972), though this latter case relied upon the use of leaf models (see below). The importance of describing the variation in momentum absorption with height in studies of lodging is, quite clearly, heavily dependent on the importance of wind in the process. For cereals and trees, of course, wind is almost always the dominant factor. However, the role of wind in the collapse of dried pea crops has been questioned in chapters 2 and 3, as the connections between plants seem to play a major part in dissipating the energy absorbed from the wind by pea crops. It may be possible to continue in the attempt to describe the variation of momentum transfer within crops by not only using a shelter factor in its calculation, but also incorporating a function relating to the variation of the density of leaf area in each level. The necessity of proceeding further with the analysis, however, seems dependent on the importance of wind in canopy collapse, and indeed, the complexity of fitting such information into any model.

In spite of the poor agreement between field measurements and laboratory estimations of momentum absorption conclusions can be drawn as to why variation of several factors between the three varieties studied in the field did not follow the pattern expected from studies with other crops. The results of Legg *et al* (1981) showed that over a season the ratio (d/h) increased and the ratio (z_0/h) decreased in bean and potato crops as leaf area density increased. Accordingly, from the results showing crop area index in chapter 2, one would expect higher values for conventional pea crops than for non-conventional crops. Values found for (C_d) above show that momentum absorption by pea plants is governed not only by the total amount of leaf present, but also by the relative amount of each leaf component present, and the manner in which it is organised. Bunches of tendrils have been found to be more efficient at absorbing momentum than leaves and stipules, largely through their more diffuse (three dimensional as opposed to two dimensional) structure. Looked at in terms of leaf structure it is thus not surprising that values for (d/h) were similar for the leafless and semileafless varieties, and greater than (d/h) for the conventional crop. The more diffuse nature of canopy elements and the increased planting density also account for similarity in ratios of (z_0/h). It also follows that the similarity between within canopy profiles for conventional and leafless crops was not to be unexpected, though the difference between these two

varieties and the semileafless in this respect remains an anomaly. The most likely explanation seems to be that, at the time of measurement, drying of the semileafless canopy was further advanced than for the others, and hence canopy structure and the profiles obtained were not strictly comparable.

The use of models (as by Thom) in similar studies is open to criticism. Sunderland (1968) has shown that the attachment of a real wheat leaf to an aluminium replica increased drag by 50% at a wind-speed of 0.50 m s^{-1} by virtue of altered surface characteristics. Also, Perrier *et al* (1973) studying the wind flow characteristics around soybean leaves and leaf models, found that the structure of the boundary layer flow over a model leaf was only comparable to that of a real leaf at low wind-speeds (up to 0.39 m s^{-1}). However, it must be recognised that using model leaves in such work does have certain advantages: they are more convenient to use as they are easier to handle, and do not suffer problems through water loss. Hence whilst there are drawbacks to using model leaves, their use, especially in conceptual studies, remains beneficial.

CHAPTER 5

MODELLING THE STANDING ABILITY OF DRIED PEA CROPS

INTRODUCTION

Measurements made on the mechanical attributes of stems and petioles, and on the forces imposed on a crop or an individual plant do not, in themselves, directly allow conclusions to be drawn concerning standing ability. For this purpose it is necessary to construct a model of some kind to allow the effect of the various forces acting on a canopy (from wind, rain, and the canopy weight) to be gauged. If the results produced seem reasonable, it may be possible to use the model to discover how standing ability may be improved effectively.

Simple models of lodging in trees and cereals of the type shown by Alexander (1971) were discussed in chapter 1. These models treat the stem as a cantilever, subject to stress from wind, rain, and canopy weight. The general mechanism by which lodging occurs, according to these models, is as follows:

i) The stem of a plant is deflected from the vertical by the wind.

ii) The torque acting at the base of the stem, due to

wind action, is increased by displacement of the canopy.

iii) Lodging takes place when the total bending moment due to these forces exceeds the resistive bending moment of the stem (to cause 'wind-snap') or the resistance offered at the soil-root interface (resulting in uprooting).

For trees and cereals much information regarding wind loading, stem strength, resilience of the soil-root interface, etc. has been gathered (eg. Grafius and Brown, 1954; Grafius, 1958; Oda *et al*, 1966; Oliver and Mayhead, 1974; White *et al*, 1976), allowing the development of more elaborate models (eg. Milne, 1986; Coutts, 1986).

Unfortunately, the canopy structure of pea crops does not lend itself to analysis in this way. Results from chapter 2 showed that, from a structural viewpoint, pea plants cannot be considered as gaining support solely from their stems; the stabilising effect of inter-plant connections must also be considered. Indeed, without this added source of stability the crop would be unable to stand at all, as is demonstrated by the necessity of using canes throughout the season to support peas grown singly or in small groups. The inter-plant connections help dissipate momentum transferred to the crop from the wind and rain, damping the motion of stems (see the discussion in chapter 3). We also know that pea crops are never uprooted (given

that they fall over in the first few weeks after germination and then grow up again, uprooting is simply not possible), and that it is likely that stems buckle under the forces acting on them before they fracture. Further differences between peas and other crops were noted in the extent and timing of lodging (see chapter 2).

THEORY AND METHODS

The manner in which pea canopies collapse is shown diagrammatically in figure 5.1, based on the observations made in the field and already discussed in chapter 2. It was observed that canopies collapsed due to failure of stems and petioles in the lowest levels of the canopy. Weakness of the petioles at this level was shown earlier in figures 2.23 to 2.28. For most varieties examined, the oldest petioles were either too weak to allow accurate measurement of Young's modulus, (Y), and the breaking moment, (M_{max}), or had already broken. At this stage the upper canopy still had a fairly rigid structure. Petioles and stems in the mid and upper canopy did not fracture or buckle until the lower canopy had reached a state where recovery was no longer possible.

The first stage in the development of any model of this nature is to define a possible mechanism, based on observations and measurements made, by which lodging

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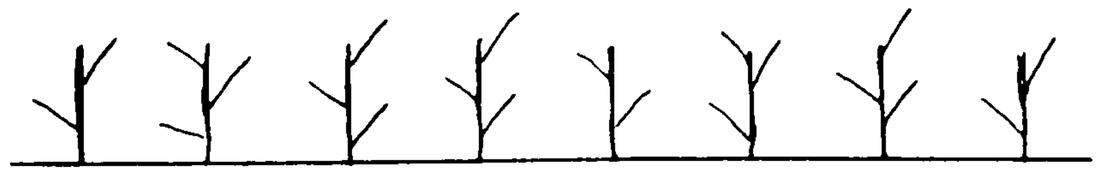

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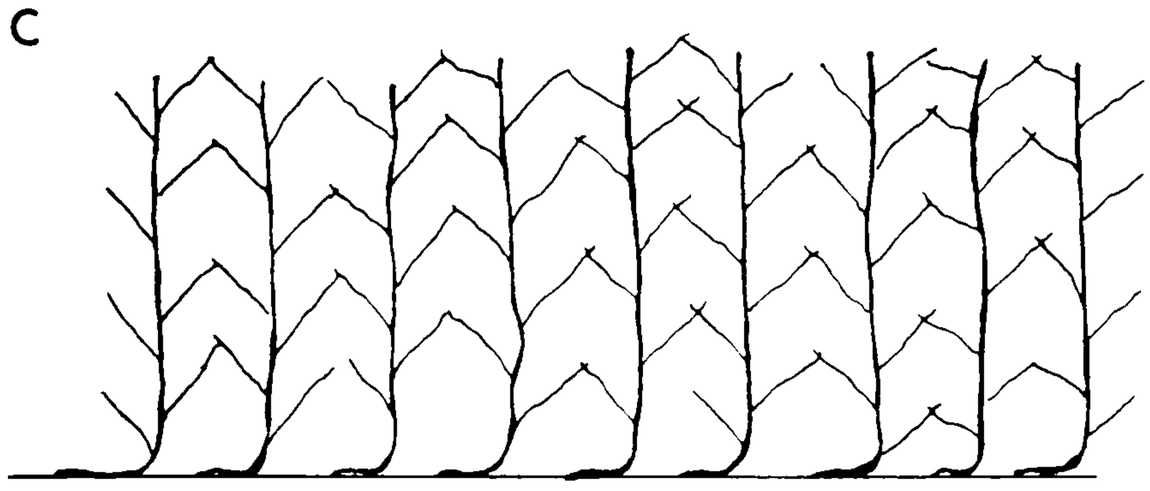

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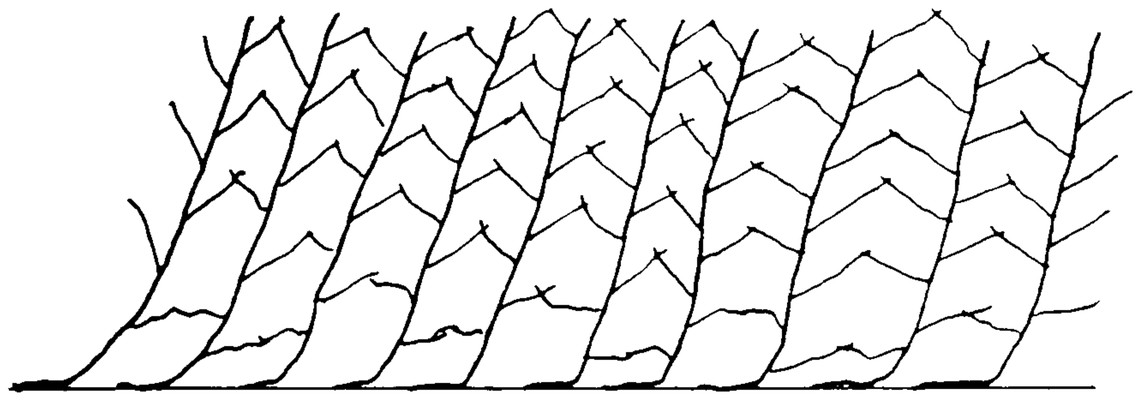

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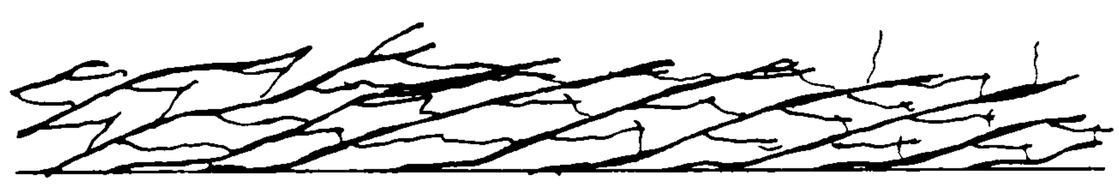

Figure 5.1 Canopy collapse of a pea crop. For a short while after emergence (a) plants grow erect with little or no support from their neighbours. This cannot be sustained for long, and the young plants soon fall and then grow upwards again (b). Once plants have petioles and tendrils large enough to reach neighbouring plants the mutual support provided allows them to stand well (c), until late in the season (d) when the structural elements, in the lower canopy especially, become weakened by senescence. The crop then falls and becomes compacted (e) before harvest.

occurs. The mechanism suggested for pea crops from the observations made above is as follows:

i) The early stages of senescence in the crop are marked by the weakening of structural elements in the lower canopy.

ii) Stability of the canopy diminishes, not only through weakening of the main stem of each plant, but also through the weakening of petioles in the lower canopy.

iii) As senescence continues, stems approach the point where they are close to buckling under the load imposed upon them.

iv) At this point buffeting of the crop by the wind becomes important. Some of the force so exerted is transmitted down through the still rigid upper levels of the canopy to the seriously weakened lower canopy, increasing the chance of buckling.

v) Stems eventually buckle and break under the weight of the canopy, with assistance from the action of wind on the crop.

The unified structure of the canopy results in collapse being uniform and simultaneous across large areas. A number of factors make the structure of a pea canopy complicated for modelling purposes:

i) The entire canopy must be treated as a single unit.

ii) The strength (and other structural characteristics) of stems and petioles varies with height above ground

and with age (see chapter 2).

iii) Tendrils can attach themselves to other bunches of tendrils, to stems or to pods on the same plant or on other plants.

iv) Petioles extend and connect to other plants in all directions.

v) The distance between plants varies.

It may seem reasonable to consider a more ideal canopy, one with a higher degree of order. For example, plants may be assumed to be evenly spaced. Tendrils might unite with other bunches of tendrils on other plants, and not with pods or stems, or with leaves from the same plant. Petioles would, perhaps, extend in only two directions, at right angles to one another. This 'idealised' canopy is still complicated to model, but comes closer to some man-made structures for which methods of analysis are available and often used in engineering. However, there is no guarantee that such simplification will produce a model that will react in the same way as a real canopy. Indeed, it is quite possible that the randomness of a pea canopy is one of its strengths (or weaknesses), and should not be done away with for the sake of convenience.

<u>Forces acting vertically</u>

It is logical to start by separating the forces involved in de-stabilisation of the crop into those that act vertically (from the weight of the canopy, the impact of

rainfall, and wetting of the canopy by the rain), and those that act horizontally (from the wind and incident rainfall). Ordinarily the forces acting vertically will compress stems lengthwise. However, when these forces are too great for the canopy to bear, stems will buckle, and, if they are unable to recover, collapse under the weight of the canopy.

From chapter 1, the load (P_E) that will cause a sample with effective length (l_E) to buckle is calculated from;

$$P_E = \frac{\pi^2 . Y . I_g}{l_E^2} \qquad 5.1$$

This may be re-written to calculate the minimum effective length of stem ($l_{E\,min}$) that will buckle under any load, (P):

$$l_{E\,min} = \sqrt{\frac{\pi^2 . Y . I_g}{P}} \qquad 5.2$$

The effective length of the sample is dependent both on the actual length of the sample and on the manner in which it is fixed at either end. Relationships between actual length and effective length for several types of end fixity were given in table 1.2. The way in which pea stems are fixed at either end (about the base and in mid-canopy) cannot be regarded as ideally pin-jointed or fully fixed. Instead at both ends the type of fixity must be somewhere between the two types. As a decision on the precise form of equation 5.2 is necessary at this stage to allow calculation of the actual length of stem that will

buckle under the vertically imposed load (l_{min}) (rather than the effective minimum length, $l_{E\,min}$) it shall be assumed that stems in a pea crop approximate to the case with one end fixed and the other pin-jointed, so that

$$l_{E\,min}^2 = 0{\cdot}5.l_{min}^2 \qquad 5.3$$

and hence equation 5.2 becomes

$$l_{min} = \sqrt{\frac{\pi^2.Y.I_g}{0{\cdot}5.P}} \qquad 5.4$$

After calculation of (l_{min}) it will be necessary to inspect the results and see whether or not values seem reasonable (ie. not so large as to make collapse primarily through buckling seem unreasonable, nor so small as to make it seem that it would not be possible for the canopy to stand at all). If they are unreasonable it will then be necessary to calculate (l_{min}) for other cases of end fixity and then to re-evaluate the results.

Another factor to consider is the series of buckling modes that may arise where some form of lateral fixing is present (see figure 1.6). In a pea crop lateral support is of course provided by the connections between plants. Given the relationship between buckling mode and load (figure 1.6) and factors such as disturbance by the wind, however, the higher modes may, as for most other practical cases, be ignored.

The weight of the canopy (F_{wc}) can be calculated from its mass multiplied by the acceleration due to gravity, (g). The additional force resulting from a thorough wetting of the canopy (F_{wR}) may be calculated similarly from the data presented in table 2.7 regarding the mass of water that may be carried by unit ground area of crop. The impact of rain or hail may be separated into a vertical component resulting from its descent through the atmosphere, and a horizontal component resulting from the deflection of droplets by the wind, effectively adding to the wind-drag on plants. The vertical component (F_{Rv}) can be calculated as:

$$F_{Rv} = m_R . v_t \qquad 5.5$$

where m_R = Total mass of rain drops incident per unit ground area per second

v_t = terminal velocity of rain drops

The total force acting vertically (F_v), in the absence of wind, on an average square metre (ground area) of the crop then becomes:

$$F_v = F_{wc} + F_{wR} + F_{Rv} \qquad 5.6$$

By dividing (F_v) by the planting density, the force acting on an average stem is found. This is then inserted into equation 5.2 to find a value averaged over the whole canopy for (l_{min}).

Forces acting horizontally

For any wind-speed at a particular height, the shearing stress exerted on a canopy is calculated from equations 3.1 and 3.7a, using results collected for the zero plane

displacement (d) and the roughness length (z_0) during the canopy drying phase. This approach is based on the assumption that neither parameter changes significantly in pea crops with wind-speed (see table 3.1). Jones (1983) calculates the horizontal momentum flux (F_{Rh}) from the rain using equation 5.5 by substituting the horizontal wind-speed just above a canopy for (v_t). The validity of this may be questioned. The horizontal velocity of a rain drop will be influenced not only by the prevailing wind-speed, but also by its size, with least effect on larger drops. As large drops are associated with heavier storms (Best, 1950) they are of greater interest than small drops. The importance of this in the model may not, fortunately, be too great, as it seems probable from calculations made by Jones (1983) that the force exerted horizontally by rain incident on a crop is small in comparison to other forces present. Given that the shearing stress and the horizontal component of rainfall are both calculated per unit ground area, the force acting horizontally on an average plant (F_H) can be found by dividing their total by the planting density. The deflection (D) of a length of stem (l) by (F_H) can then be found from equation 2.2, provided that the limits of applicability of this relationship (see chapter 2) are not exceeded.

Estimating the improvements in the mechanical attributes of pea stems necessary to give better standing ability.

So far these calculations seem far removed from considering the crop as a single, unified structure, as is required for the model to be realistic and at all useful. However, it should be possible to estimate the necessary improvements in the mechanical attributes of stems by comparison of the results gained for the leafless variety Filby from equations 2.2, and 5.2 to 5.6 with those obtained for non-leafless phenotypes. In both the 1983 and 1984 field seasons Filby was found to be capable of remaining erect until, or very nearly until, harvest (see above). Accordingly the aim of work intended to improve the standing ability of pea crops is, in effect, to make conventional or semileafless varieties stand as well as Filby. It is reasonable to suppose that by improving the mechanical charactersitics of stems of non-leafless plants to the point where (l_{min}) and (D) are similar to the values found for Filby, these crops should be able to stand as well as the leafless variety. For the purpose of comparison between varieties, the absolute value of (D) is not required. Hence the length of stem for which it is calculated (equation 2.2) is arbitrary, so long as the same value is used throughout.

The main assumption involved in this model is that the stabilising effect of connections between plants, and

their ability to dissipate momentum transferred to the crop from wind and rain are similar for all three phenotypes. The basis for this assumption, and its applicability to semileafless and conventional canopies are both discussed below.

Maximum wind-speeds and rainfall intensities likely to be encountered by a pea crop in the U.K.

Mean figures for rainfall or wind-speed over extended periods are of very little interest in lodging studies (Shaw, 1982), as they do not show the maximum stress that a plant or canopy will have to withstand. It is therefore necessary to consider the heaviest rainfall and highest wind that a canopy may be expected to encounter.

Jackson (1977; 1979; 1985) calculated the maximum rainfall likely in the U.K. for periods of between 1 hour and 5 hours. The highest intensity recorded in Britain occurred during a storm over southern England in June, 1910 at Caversham near Reading when approximately 124 mm fell in an hour (Mill, 1910). Fortunately rainfall of this severity is extremely rare and very localised. Unfortunately, however, the highest intensity rainfalls occur during summer thunderstorms from early June to early October, covering the time when many crops are most vulnerable to lodging. Jackson (1985) calculated the probability of any monitoring station in any year detecting similar intensities to that measured at

Caversham in 1910 as less than 10^{-6}. It would be inappropriate for a study of this nature to consider such a rare occurrence, and instead events likely to occur within a more reasonable time-span will be considered. The peak rainfall expected to occur with a probability of once in 5 years for most sites in England is between 16 and 20 mm/hour (NERC, 1975).

Published monthly values of the highest hourly mean wind-speed and highest recorded gust for a number of sites in the U.K. are given in the Monthly Weather Report (H.M.S.O., London) from 1971 onwards. For the pea growing areas of Britain means, maxima and minima have been calculated from these data for hourly means and highest gust speeds for the period June to August (table 5.1).

For any particular site a good approximation of maximum gust speed may be obtained from the results of Hardman *et al* (1973) who gave maximum gust to mean hourly wind-speed ratios of 1.5, 1.7, 1.9 and 2.1 for 4 classes of terrain from open, level, unobstructed country to very rough surfaces such as towns. Oliver (1974) found a value for this ratio of 2.0 for a coniferous forest. From the data used for the pea growing areas of the country a mean value of 1.67 was found.

Values given in the Monthly Weather Report are measured at a height (or effective height) of 10 m. Given the

Table 5.1 Mean, maximum and minimum values of the highest hourly mean wind-speed and highest gust speeds at an effective height of 10 m for the pea growing areas of the United Kingdom between June and August. Data were taken from the Monthly Weather Report (H.M.S.O., London) for the five years from 1976 to 1980.

	Mean hourly wind-speed ($m\ s^{-1}$)	Maximum gust speed ($m\ s^{-1}$)
Mean	20	33
Maximum	27	41
Minimum	13	27

relationships between fetch and the boundary layer that is fully adjusted to the underlying surface discussed in chapter 3 it is of course unreasonable to extrapolate the wind profiles measured over pea crops to this height for micrometeorological purposes. For the purpose of this study, however, exact values of extreme winds are not required. What is required is some idea of the maximum wind-speed likely to be encountered over the pea growing areas of Britain within, say, a five year period. Using the values of (d) and (z_0) found for Maro, Filigreen and Filby in chapter 3, and a wind-speed of 40 m s^{-1} at the height 10 m (in accordance with the values given in table 5.1) the wind-speed at 2 m for all three species is approximately 26 m s^{-1}. Accordingly this wind-speed at the height 2 m was used in the calculations of shearing stress for each phenotype in the model. A worked example of the calculation of shearing stresses for this purpose is given in appendix IV.

RESULTS

The model has been applied in full using measurements made in the previous chapters to the varieties Maro, Filigreen and Filby. Results from the varieties Sentinel and Progreta, widely recognised by breeders and growers as having stiffer than average stems and improved standing

ability in comparison to other conventional and semileafless varieties (see chapter 2), were also considered.

The forces acting horizontally and vertically caused by the transfer of momentum from rainfall to the crops are presented for a broad range of rainfall intensities from 0 to 60 mm h^{-1} in figure 5.2. This covers the full range likely to be encountered in the pea growing areas of the U.K.

Forces acting on canopies of the three phenotypes, based on these results and the canopy mass data of chapter 2, are shown in table 5.2. The wind-speed used for calculation of shearing stress in this table was 40 m s^{-1} at 10 m. (τ) was calculated following the method given in the worked example in appendix IV (see also above). The rainfall intensity used was 20 mm h^{-1}. These values were chosen as being typical of the maxima likely to be encountered in the pea growing areas of Britain, during the critical phase of crop development when lodging occurs, at any site over a 5 year period (see above). The total force acting horizontally is lower in all cases than that acting vertically, most notably for the conventional crop. For forces acting in both directions total values are highest for the conventional crop, and least for the leafless variety.

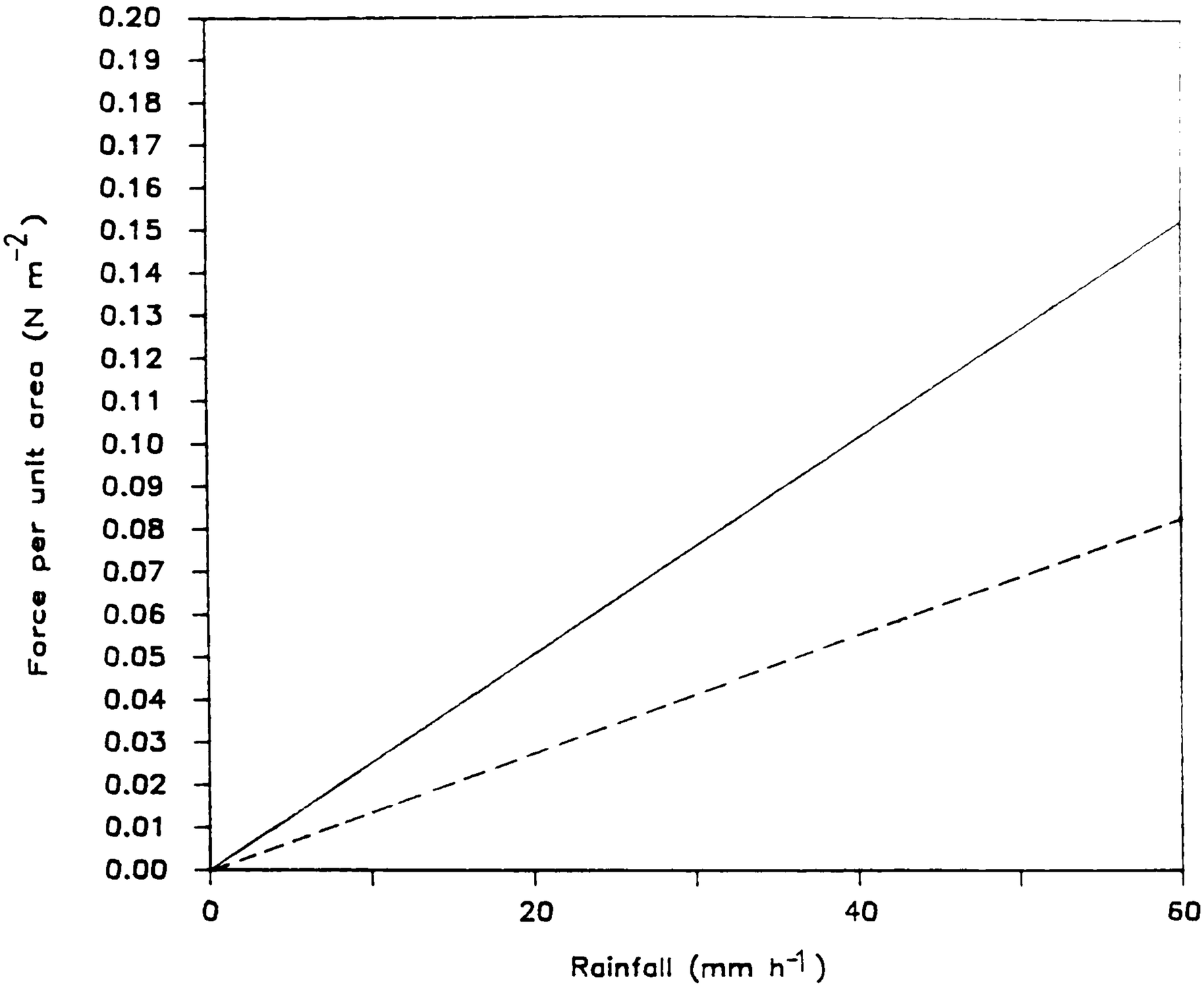

Figure 5.2 The force exerted per unit ground area due to momentum transfer from rain falling on a crop with intensities ranging from 0 to 60 mm h^{-1}. (————) represents the vertical component, (F_{Rv}), with (v_t) equal to 9.2 m s^{-1} (terminal velocity for large rain drops). (– – – – –) represents the horizontal component (F_{Rh}) calculated for a wind-speed of 5 m s^{-1} just above the canopy.

Table 5.2 Forces acting vertically, due to canopy weight (F_{wc}), thorough wetting of the canopy (F_{wR}), and incident rainfall (F_{Rv}), and those acting horizontally, due to the wind (τ), and rainfall (F_{Rh}), on pea canopies of contrasting leaf form, with total forces for either direction. Where available, standard errors are given. All forces are expressed in N m^{-2}. (τ) is calculated for a wind-speed of 40 m s^{-1} at 10 m (see the worked example in appendix IV), and forces due to rainfall are calculated for an intensity of 20 mm h^{-1}.

Vertical forces	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
F_{wc}	48.1 (± 1.9)	39.2 (± 2.0)	23.5 (± 2.0)
F_{wR}	2.5 (± 0.5)	2.0 (± 0.8)	4.7 (± 1.7)
F_{Rv}	0.07	0.07	0.07
Total (F_v)	50.67 (± 2.4)	41.30 (± 2.8)	28.29 (± 3.7)
Horizontal forces			
F_{Rh}	0.03	0.03	0.03
τ	10.46 (± 0.26)	10.14 (± 0.66)	9.41 (± 0.49)
Total (F_H)	10.49 (± 0.26)	10.17 (± 0.66)	9.44 (± 0.49)

Comparison of the forces exerted due to the transfer of momentum from falling rain drops to a crop, with those due to the wind or the weight of the canopy, show that the impact of rainfall on plants is relatively unimportant in canopy collapse. This was substantiated during the 1984 field season during a thunderstorm when 52 mm of rain fell in an hour and forty minutes (a mean intensity of 31 mm h^{-1}) on June 20th. The leafless crop appeared completely unaffected. The two conventional varieties (Maro and Birte) were also largely unaffected. However, the semileafless variety Filigreen did start to lodge around this time. Whilst this is an early maturing variety, and hence will lodge earlier than later varieties in any case, it seems probable that the exact date for lodging was brought forward slightly by the storm. Given the relative magnitudes of the forces involved, however, this was due more to the extra weight caused by wetting of the canopy than it was to the impact of raindrops.

Based on these results and the measurements of (Y) and (I_g) of pea stems from the lower canopy in chapter 2 (figures 2.20 to 2.25), (l_{min}) was calculated for the three varieties (see table 5.3). Also shown for each variety is the calculated deflection (D) of an isolated sample of stem 50 mm long subjected to the horizontal load shown in table 5.2.

Table 5.3 Calculation of the improvement necessary in the flexural rigidity ($Y.I_g$) for the varieties Maro (conventional) and Filigreen (semileafless) to withstand the forces acting on these crops to the same degree as the leafless variety Filby.

	Maro (conventional)	Filigreen (semileafless)	Filby (leafless)
I_g (mm^4)	2.3 (± 0.7)	2.0 (± 0.7)	2.3 (± 0.8)
Y ($N\ mm^{-2}$)	162.2 (± 15.8)	171.0 (± 15.8)	200.5 (± 16.4)
Vertical component			
l_{min} (mm)	98.0 (± 17.5)	130.0 (± 29.6)	178.2 (± 47.1)
% improvement in ($Y.I_g$) required	230.4	87.9	-
Horizontal component (calculated for a sample 50 mm long)			
D (mm)	18.1 (± 3.0)	12.0 (± 2.0)	8.7 (± 1.5)
% improvement in ($Y.I_g$) required	101.7	37.1	-

The required improvement in ($Y.I_g$) for stems from Maro and Filigreen seems, at first sight, to be very large, especially to cope with the forces acting vertically. For the purpose of breeding varieties of pea with improved standing ability it is also useful to have some idea of how the calculated required increase in ($Y.I_g$) translates into increased stem wall thickness and increased cross sectional area of stem wall (based on the measurements made in chapter 2). Accordingly the required increase in stem wall thickness and cross sectional area were calculated, assuming that (Y) and the dimensions of the central cavity of the stem remained unchanged. These results are presented in table 5.4. The increase in area is of most relevance as it refers more directly to the increase in the amount of stem wall material required. It must be noted, however, that the results shown in this table should be treated with some caution as there is no guarantee that (Y) will not decrease as (I_g) increases (see below).

Values of (l_{min}) and (D) for Sentinel (stiff stemmed semileafless) and Progreta (tare-leaved rogue) are shown in table 5.5. Forces acting on crops of these two varieties were calculated from the results of canopy mass from the microplots at Morley, (figure 2.16), stress due to falling rain (from figure 5.2), and the values given for the amount of water carried by crops of differing leaf types in table 2.7. (I_g) and (Y) were taken from figures

Table 5.4 Increase of stem wall thickness and cross sectional area of stem wall required to give the necessary % improvement in ($Y.I_g$) through an increase in (I_g) alone, from the figures shown in table 5.3. Calculations are based on the measurements of the internal and external dimensions of stems made in chapter 2.

	Stem wall thickness (mm)	required % increase in wall thickness	required % increase in cross sectional area of stem wall
Vertical component			
Maro	0.64	69.1	105.6
Filigreen	0.59	34.6	48.5
Horizontal component			
Maro	0.64	37.6	53.8
Filigreen	0.59	16.6	22.3

Table 5.5 Calculation of (l_{min}) and (D) for the varieties Progreta (tare-leaved rogue) and Sentinel (stiff stemmed semileafless), from the data on canopy mass, (Y), and (I_g) for both varieties given in chapter 2. Values for Filby are included for direct comparison. % improvements in ($Y.I_g$) for Progreta and Sentinel to match Filby are included where necessary.

	Progreta (rogue)	Sentinel (stiff stemmed semileafless)	Filby (leafless)
I_g (mm^4)	3.9 (± 1.1)	2.7 (± 0.7)	2.3 (± 0.8)
Y ($N\ mm^{-2}$)	195.0 (± 27.2)	173.0 (± 27.8)	200.5 (± 16.4)
Vertical component			
Total F_v	36.3 (± 3.8)	25.1 (± 2.9)	28.3 (± 3.7)
l_{min} (mm)	162.9 (± 39.8)	191.0 (± 44.3)	178.2 (± 47.1)
% improvement in ($Y.I_g$) required	19.7	-	-
Horizontal component (calculated for a sample 50 mm long)			
D (mm)	8.8 (± 1.6)	8.6 (± 1.1)	8.7 (± 1.4)
% improvement in ($Y.I_g$) required	1.2	-	-

2.22 and 2.25. For calculation of (D), Progreta was assumed to have similar momentum absorption properties to Maro, and Sentinel to Filigreen (based on their leaf type and planting densities). Differences between Progreta Sentinel and Filby with respect to their ability to cope with the horizontal load were negligible. The calculated value of (l_{min}) was lower than Filby for Progreta, but, surprisingly, higher for Sentinel. It was remarked in chapter 2 that the measured masses of plants in the microplots seemed low in comparison to their counterparts in the field plots, and that it was likely that they had been harvested at a more advanced stage than had plants from the field plots. If this was so, then the results for calculated values of (l_{min}) given above are misleading. (l_{min}) has thus been recalculated using (I_g) and (Y) values measured for Sentinel and Progreta, with the canopy masses measured for Filigreen and Maro respectively (see table 5.6). For these results (l_{min}) is lower in both cases than the value calculated for Filby. The percentage improvement necessary in ($Y.I_g$) is substantially reduced in comparison to the values shown for Maro and Filigreen in table 5.3. Necessary increases in stem wall thickness and cross sectional area of stem wall from the results of table 5.6 are given in table 5.7.

Table 5.6 Calculation of (l_{min}) and (D), using values of the vertical component of load from Maro and Filigreen (see table 5.2) with values for (Y) and (I_g) from Progreta and Sentinel respectively. Values for Filby are included for direct comparison. % improvements in ($Y.I_g$) for Progreta and Sentinel to match Filby are included where necessary.

	Progreta (rogue)	Sentinel (stiff stemmed semileafless)	Filby (leafless)
I_g (mm^4)	3.9 (± 1.1)	2.7 (± 0.7)	2.3 (± 0.8)
Y ($N\ mm^{-2}$)	195.0 (± 27.2)	173.0 (± 27.8)	200.5 (± 16.4)
Vertical component			
Total F_v	50.6 (± 2.4)	41.3 (± 2.8)	28.3 (± 3.7)
l_{min} (mm)	137.9 (± 30.9)	148.9 (± 32.0)	178.2 (± 47.1)
% improvement in ($Y.I_g$) required	66.9	43.2	-

Table 5.7 Increase of stem wall thickness and cross sectional area of stem wall required to give the necessary % improvement in ($Y.I_g$) through an increase in (I_g) alone, from the figures shown in table 5.6. Calculations are based on the measurements of the internal and external dimensions of stems made in chapter 2.

Vertical component

	Stem wall thickness (mm)	required % increase in wall thickness	required % increase in cross sectional area of stem wall
Progreta	0.73	26.5	37.1
Sentinel	0.85	15.0	22.8

DISCUSSION

The model agrees with much of what we now know about standing ability of the varieties grown in the field plots at Morley (Maro, Filigreen, and Birte). Values found for the minimum length of stem that will buckle under the vertical load imposed (l_{min}), are of the correct order of magnitude to allow collapse to be due, primarily, to buckling of stems in the lower canopy. The assumption that the end fixity condition of stems approximates to that where one end is fixed and one pin-jointed seems reasonable as (l_{min}) is of the correct order of magnitude for lodging to occur through buckling of stems in the lower canopy. Also, Filby, the leafless variety which has shown itself to be capable of staying upright until harvest, had the best figures for (l_{min}) and (D) for the three varieties grown in the field plots. The calculated improvements in ($Y.I_g$) seem sensible; they are neither so small as to appear inconsequential nor so large as to make one wonder how the canopies managed to stand erect in the first place!

Results shown in table 5.5, for the comparison of the stiffer stemmed varieties Sentinel and Progreta with Filby, contradicted the model by predicting a higher value of (l_{min}) for Sentinel than Filby. Also, the value for Progreta is within one standard error of the value for

Filby. There is good reason, however, for believing that the canopy masses measured in chapter 2 for these varieties were measured at a later stage than were the values for plants in the field plots. If this is true, then the figures given in table 5.6 (using canopy masses from Maro and Filigreen) are a better indication of the relative strength of canopies of these two varieties in comparison with Filby. This is clearly a matter that needs more investigation, as it may either further substantiate, or invalidate, the model described. Results for Sentinel and Progreta emphasise the importance of timing when measuring details of canopy structure in lodging studies for pea crops. It is certainly preferable not to rely solely on measurements taken on plants grown in microplots as it is very difficult to accurately estimate the time when lodging would occur in crops of these varieties. In addition, the artificial support provided throughout the season is likely to affect results. The technique of artificially supporting plants grown in the open just before collapse is expected, seems preferable.

The major factor causing lodging of pea canopies has been shown to be the inability of the load bearing elements within a crop (stems and petioles) to carry the weight of the canopy once the plants start drying out in the period leading up to harvest. Wind certainly plays a part in this, though the small difference between the total force

exerted by the wind upon varieties that lodge, and Filby (that does not), is insufficient on its own to explain the difference in standing ability. Also, crops of Sentinel and Progreta appear as well equipped as Filby to withstand forces acting horizontally, despite the fact that they are far from being resistant to lodging. A major difficulty in defining the exact effect of the wind arises through the role played by the connections between plants. The fact that much of the energy transferred to pea canopies through momentum absorption will be dissipated within the connections between plants, and hence will probably have little effect on the stems has already been discussed. For this reason it is very difficult to unite the effects of forces acting horizontally with those acting vertically, and, accordingly no direct attempt has been made here. Provided that the assumption that the mutual support and momentum dissipatory capabilities offered by inter-plant connections are similar in the phenotypes studied, is correct, however, the model should be little affected by this complication.

Estimates of the improvement required in (I_g) to achieve the calculated necessary increase in ($Y.I_g$) are only approximate, as the behaviour of (Y) as (I_g) changes is unknown for pea plants. Oda *et al* (1966) found that (Y) decreases as (I_g) increases. The most likely explanation for this is that the amounts of different cell types making up the stem change relative to one another as (I_g)

changes. For example, it should not be expected that the number of vascular bundles will increase just because the amount of parenchyma in the stem has increased, or vice-versa.

Standing ability may, possibly, be improved in a number of ways other than by increasing ($Y.I_g$). Most other methods, however, are complicated by consideration of the likely effect on yield. For example, if canopy mass were to be reduced, yield would obviously suffer unless there was a corresponding increase in harvest index, which is most unlikely. Reducing canopy height, used to such great effect in the breeding of cereals with superior standing ability, would apparently have little effect for a pea crop, other than by reducing total canopy mass. Increased planting density would provide more stems to support the canopy, though the strength of stems may be reduced as a result of the increased competition. In any case, there have already been a number of studies to assess optimum planting densities for economic yield (Hedley and Ambrose, 1981; Ambrose and Hedley, 1984), and it seems doubtful that any improvement in standing ability at high density would substantially improve yield. The possibility of using nurse crops was mentioned in chapter 1. Lovelidge (1987) has reported very promising results for mixtures of peas with spring barley. The model has not been used to predict the advantage that may be conferred by the use of nurse crops for a number of reasons. The only available

information on values of (Y) and (I_g) for cereals is that of Tani (1963) and Oda *et al* (1966). In recent years there has been little interest in the mechanical attributes of cereal stems (as good standing ability has already been achieved), and hence there are no data available for the more modern varieties. The degree of competition within a canopy will be affected by the introduction of a nurse crop (Snoad, 1983), and, as is the case for increasing planting density, it is unknown what effect this may have on the strengths of stems and petioles. The reliability of the model, essentially developed for a homogeneous canopy (calculations are of the mean load acting on an average stem, assuming similar degrees of mutual support between crops) may be open to doubt when comparing results from a leafless monoculture with those for a mixed crop.

The assumption that the model is largely based on is that the stabilising effect of inter-plant connections is similar in the three phenotypes studied. This seems reasonable for the comparison of semileafless and leafless plants, though perhaps somewhat less so for the comparison of leafless and conventional varieties. Similar numbers of inter-plant connections per plant throughout the canopy were shown earlier in figure 2.14 for the four varieties grown in the large field plots (Maro, Birte, Filigreen and Filby). Semileafless and leafless varieties are sown at approximately the same density, and have similar leaves

(ignoring the stipules which do not help in supporting the canopy). Conventional plants are sown at a lower rate (about 65 plants m^{-2} instead of around 100 plants m^{-2}), and their leaves contain fewer tendrils than do leaves of the other phenotypes. It is possible therefore, that the estimate of the required improvement for conventional plants is rather low. From a practical viewpoint this matters little as the results show that semileafless varieties require a smaller improvement in stem characteristics, and most breeders already prefer them anyway.

The models presented by other authors to explain and predict lodging of trees and cereals (eg. Alexander, 1971; Grace, 1977; Jones, 1983; Milne, 1986; Coutts, 1986) are clearly not relevant to pea canopy collapse. The mechanism by which they predict lodging to take place does not occur in a pea crop. Equally, the mechanism proposed here for the collapse of pea crops (ie. mostly through buckling of stems) will not occur in species with much stronger and thicker stems, and where plants interact with their neighbours in only a limited way.

The results demonstrated the small effect that rain plays in lodging, and agree with similar calculations by Jones (1983), showing that momentum absorption from the horizontal component of rainfall is only a small fraction of that from the wind. The force exerted vertically by

rain is probably over-estimated for leafless varieties as these never achieve full ground cover (see, for example the radiation interception studies in Pyke, 1983, and MacKerron and Thompson, 1983). Also, the rainfall intensities used in the calculations were mean hourly values (albeit for the heaviest rain events likely in a 5 year period), rather than the maximum intensities that may occur within such storms. Like the uncertainty concerning the horizontal velocity of falling rain drops mentioned above, both seem safe to ignore due to the very limited impact (less than 1%) that falling rain has in comparison to the other forces involved.

Hail damage, however, has been reported for many crops including soybeans, maize and wheat (Changnon, 1971), barley (Gilbertson and Hockett, 1979), cotton (Makhumudov, 1981) and oilseed rape (McGregor, 1980). Morgan and Towery (1976) and Towery *et al* (1976) have shown that, as would be expected from the models of Alexander (1971) etc., hail damage is increased by high wind-speeds. Hail damage is greater than rain damage due to differences in the momentum carried by hailstones and rain drops. The size of rain drops is limited to a maximum of 5.8 mm (Ward-Smith, 1984). However, the size of hailstones is not so limited due to the manner in which they are formed within clouds, the largest reliably recorded one being 140 mm in diameter and weighing 766 g! Typical hailstones are similar in size to the largest raindrops (about 5 mm),

though in regions where hail storms are frequent, stones of 20 mm are not uncommon (Ward-Smith, 1984). Whereas the terminal velocity (v_t) of a raindrop 5.5 mm in diameter is 9.2 m s^{-1}, (v_t) for a hailstone with a diameter of 20 mm is 17.3 m s^{-1} (Ward-Smith, 1984). The momentum carried by such a hailstone will be approximately 16 times that carried by the largest possible rain drop. Thus a direct hit on a single plant with only limited support from its neighbours by a large hailstone may be enough to cause lodging or other serious damage. For a pea crop, however, the momentum from hailstones will be dissipated throughout the canopy, and may have little more effect on canopy collapse than normal rainfall of a similar intensity.

CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS TO BREEDERS

In recent years, as E.E.C. cereal surpluses have reached massive proportions, the dried pea crop has become established as one of the most important 'alternative' crops in western Europe. Having declined greatly in its importance in the post-war years, dried peas have recovered to become the sixth largest crop (by area sown) in the U.K., after wheat, barley, potatoes, oilseed rape and sugar beet (MAFF, 1987) with over 100,000 hectares in 1987. Further expansion of the crop is certain. Lodging is currently the most serious problem confronting pea growers (Heath and Hebblethwaite, 1985 b). The problem originates from the growth habit of the wild pea, which uses other plants or objects for support. When grown as a monoculture peas are too weak to fully support themselves and one another when stems and petioles weaken as the crop dries in late season. Lodging is inevitable in almost all varieties. An assessment of standing ability by the Processors and Growers Research Organisation (PGRO, 1984 b) gave only 3 varieties (including the leafless Filby), out of 29 recommended to farmers, a score higher than 2 on a scale of 0 to 5. Based on an average yield of around 3 t/ha, the current price of about £190 per tonne

and minimum loss of 10% (Snoad, 1980) for non-leafless varieties, the minimum annual loss nationally due to lodging alone is around £6 million. The actual loss every year is likely to be much greater, and in bad years makes the crop very uneconomic.

It thus seems odd that there has been no prior study of the forces and other factors involved in this serious problem. As long ago as 1919 Garber and Olson considered the implications of the morphological characters of cereal stems for lodging. A steady stream of work followed which eventually led to the breeding of varieties with a much higher resistance to lodging (Austin, 1980). The lack of research into the problems concerned with standing ability of dried pea crops, however, has prevented a precise definition of what breeders should be aiming for, and little progress has so far been made.

The work presented above has considered the manner in which the various forces acting on pea canopies cause collapse and has also considered ways in which standing may be improved. It has been shown that the crop collapses due to stems and petioles weakening late in the season and buckling under the weight of the canopy. The force exerted by the wind is certain to influence lodging, but does not appear to play a very major role. This is due to the efficient dissipation of absorbed momentum through the network of connections between plants formed

by the tendrils. Rain plays only a minor role in canopy collapse, a heavy fall may bring the date of lodging forward by no more than a few days due more to the increased weight of a wet canopy than to absorption of momentum from intercepted raindrops. For most varieties, therefore, lodging in pea crops may be regarded as more a part of the developmental process than a result of environmental conditions. This was evident by the fact that it was possible, towards the end of the 1984 season, to predict beforehand when canopy collapse would occur, and then to install extra support to allow measurements that would be properly representative of the structure of pea crops at lodging.

The good standing ability of leafless varieties was utilised in the model developed in chapter 5. Despite the fact that low yields of such varieties due to reduced photosynthetic area (MacKerron and Thompson, 1983) make them unsuitable for continued development in breeding programmes, their good standing ability suggests that it may be possible for dried pea crops of other phenotypes to stand until harvest, once breeders concentrate on improving the structural characteristics of stems and petioles. Direct comparison of other pea crop phenotypes with a leafless crop in the model has enabled estimation of the increase in the flexural rigidity ($Y.I_g$) necessary

to improve standing ability. This approach avoided the necessity of describing the complicated structure of the crop in depth.

The results of the model suggest that the best way to improve standing ability in peas is by improving the mechanical attributes of stems and petioles. Increasing Young's modulus (Y), the second moment of area, (I_s), and the critical bending moment, (M_{max}) should, hopefully have little adverse effect on yield. Other potential methods (reducing canopy mass, increasing planting density, etc.) all appear to have undesirable implications for yield and thus seem less worthwhile. Improvement in (I_s) will be achieved by increasing the area of stem wall relative to the total cross sectional area of the stem, and by increasing the outer diameter of stems. (Y) for the stem as a whole will be improved through an increase in those cell types that contain greater quantities of the materials (eg. lignin) which have higher values of (Y), relative to the cell types that contain lesser amounts of these substances.

The scope for improvement in these respects is unknown as there has been, lamentably, no thorough screening of varieties and cultivars of peas to date. Oda *et al* (1966) examined 112 varieties of wheat, and 95 of barley from all over the world. A screening programme of this magnitude will provide much valuable information and should allow

much better exploitation of the available resources. Conclusions may also be made about the relationship between some aspects of stem structure and stem strength.

Little difference was found between varieties of the conventional, semileafless and leafless phenotypes with respect to their efficiency as crops to absorb momentum from the wind. Though this appeared at first rather surprising (in view of the great differences in leaf type and leaf area present), investigations in the wind-tunnel of the Department of Forestry and Natural Resources at the University of Edinburgh showed that individual leaves from leafless plants were more efficient (on a unit area basis) in absorbing momentum than were leaves from conventional plants. Wind was ruled out as the governing factor in lodging from the results of the model, as differences in the ability to withstand the forces acting horizontally between the varieties Maro, Filigreen and Filby were small. Also, the stiffer stemmed varieties Sentinel and Progreta, despite the fact that their standing ability is not as good as Filby's, appear equally well equipped to cope with these forces by virtue of having superior values of $(Y.I_g)$.

Several differences have been shown between lodging in cereals and trees and that of peas. Pea canopies collapse completely in the final weeks before harvest every season, through failure of their canopy structure. Lodging in

trees and cereals is much rarer, generally occurs in patches and usually by uprooting. In trees and cereals it occurs as a result of the wind repeatedly forcing plants to sway to and fro, eventually either fracturing the stem or loosening the root plate so much so that uprooting occurs. In peas the structural elements at the base of the canopy simply become too weak to support the weight of the canopy. To differentiate between the two cases it may be better to refer to lodging in peas with the more descriptive phrase 'canopy collapse', as has been done in the title of this thesis.

It should be remembered that the results describing the canopy structures presented in chapter 2 refer to a limited number of varieties and are not necessarily representative of canopy structure in other varieties. Also the yields in the plots used at Morley in 1984 were lower than the national average (under 2 tonnes/hectare as opposed to in excess of 3 tonnes/hectare). Using these results, however, the model of standing ability presented in chapter 5 predicted that, of the varieties studied, Filby had the best standing ability (on the assumption that the proposed mechanism for canopy collapse is correct), and Maro and Filigreen (conventional and semileafless respectively), the worst, in accordance with the observations made here and by other workers.

The results of this work have shown some previous comments found in the literature to be misleading. Murphy (1983) stated that pea crops in Ireland fall due to the wet weather. It was shown in chapter 5 that the contribution of incident rainfall to the forces acting on pea crops is negligible in comparison to other forces, in agreement with the calculations made by Jones (1983) for cereals. At most it appears as though rain may bring canopy collapse forward a few days through an increase in canopy weight. Also, Snoad (1980) commented that plants with thin stems are to be preferred to those with thicker stems, though this was later revised (Snoad, 1985). Oda *et al* (1966) reported an increase in (I_g) in some varieties in spite of a reduction in overall culm diameter. Whilst this may explain Snoad's remark concerning the alleged desirability of pea plants with thin stems, to achieve the necessary increase in (I_g) it seems certain that the external diameter of stems must be increased.

It is clear that the strength of pea stems and petioles decreases as plants senesce. Bartel (1937) reported weakening of cereal stems as crops approached maturity. Grafius *et al* (1955) reported that stem fracture only occurred in cereals when plants were dead-ripe or infected with *Septoria*. Therefore, in addition to taking measurements of the mechanical attributes of the plants as they collapse, changes of (Y) and (I_g), and of finer structural detail should be monitored over the whole

season. Results from this work should identify the critical changes that occur in stems that lead to canopy collapse.

Whilst some of the necessary screening work can be done using plants grown in the greenhouse, it must be remembered that environmental effects on structural attributes of plants have been found (Grace and Russell, 1977), and hence it is essential to also take measurements on plants grown in the field (and even then preferably at a number of different sites). As canopy structure changes so rapidly in the critical period (mid-June to late July), and as measurements must be made on fresh material, additional technical help will be essential to cope with the work load at this time.

APPENDIX I

Weather conditions at the Norfolk Agricultural Station, Morley St. Botolph, Norfolk. March 1st to August 15th 1984

Daily mean, maximum, and minimum temperatures, rainfall, and sunshine hours are presented in figures A.1 to A.5, from data recorded over the 1984 field season at the experimental site (the Norfolk Agricultural Station, Morley St. Botolph, Meteorological Office Recording Station No. 3063). Data are for the period 1st March (two weeks before sowing) to August 15th (just after harvest). Also shown, in table A.1, are the monthly mean temperatures, and sunshine and rainfall totals for 1984 with the 18 year averages for comparison.

Mean temperatures for the season were around or slightly above the 18 year means, whilst monthly mean, maxima, and minima were both slightly less than average. Rainfall totals were close to the 18 year means for March, May, July, and August. However, due to a drought from April 10th to May 20th rainfall in April was well below the norm. The total for June was almost twice the average as a result of a thunderstorm on June 20th when 52 mm of rain fell in only 1 hour and 40 minutes. Total sunshine hours were close to the average for the second half of the season, though below average in March and May and well above the mean in April.

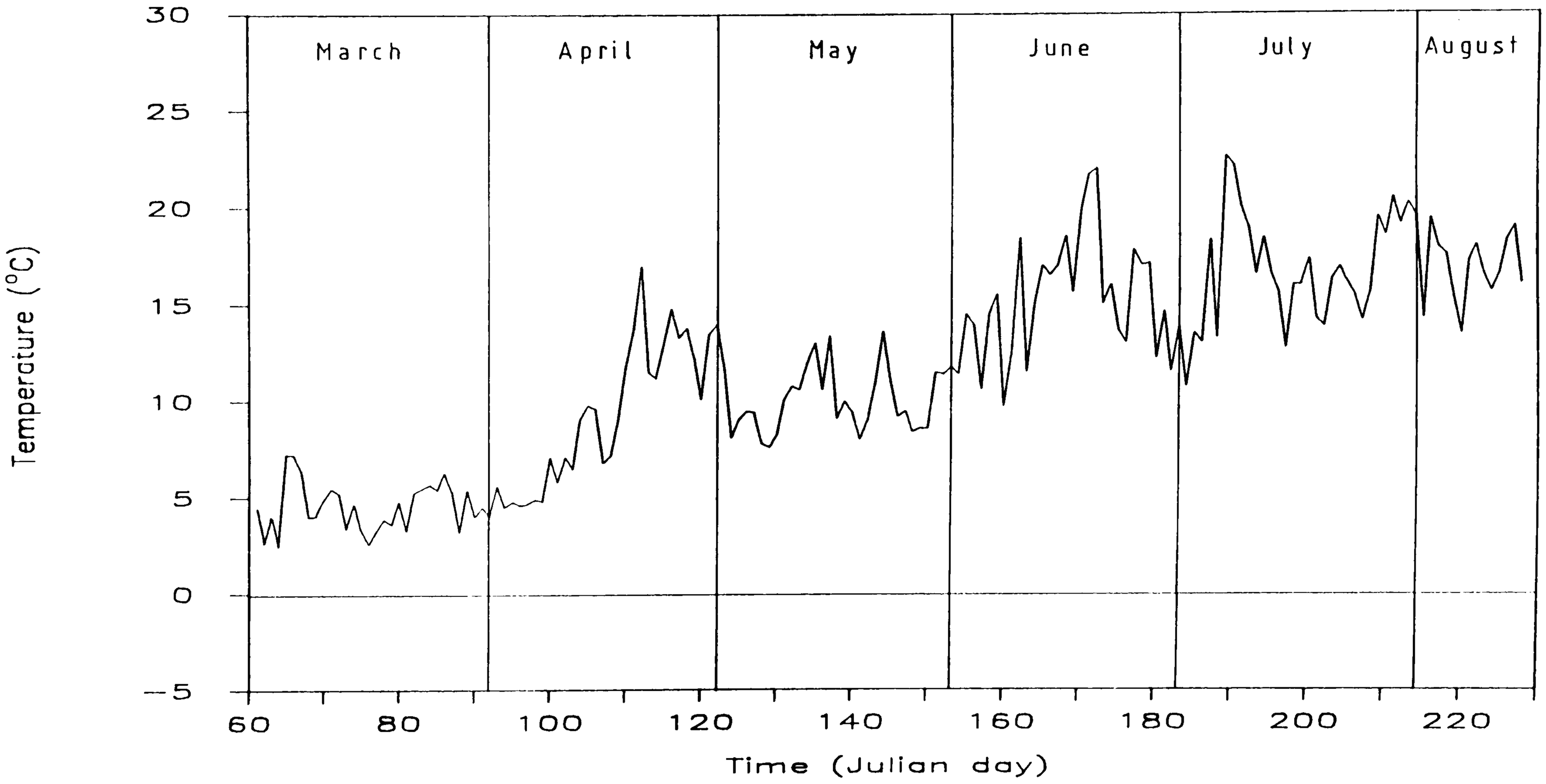

Figure A.1 Daily mean values for temperature at the Norfolk Agricultural Station, Morley St. Botolph for the 1984 field season.

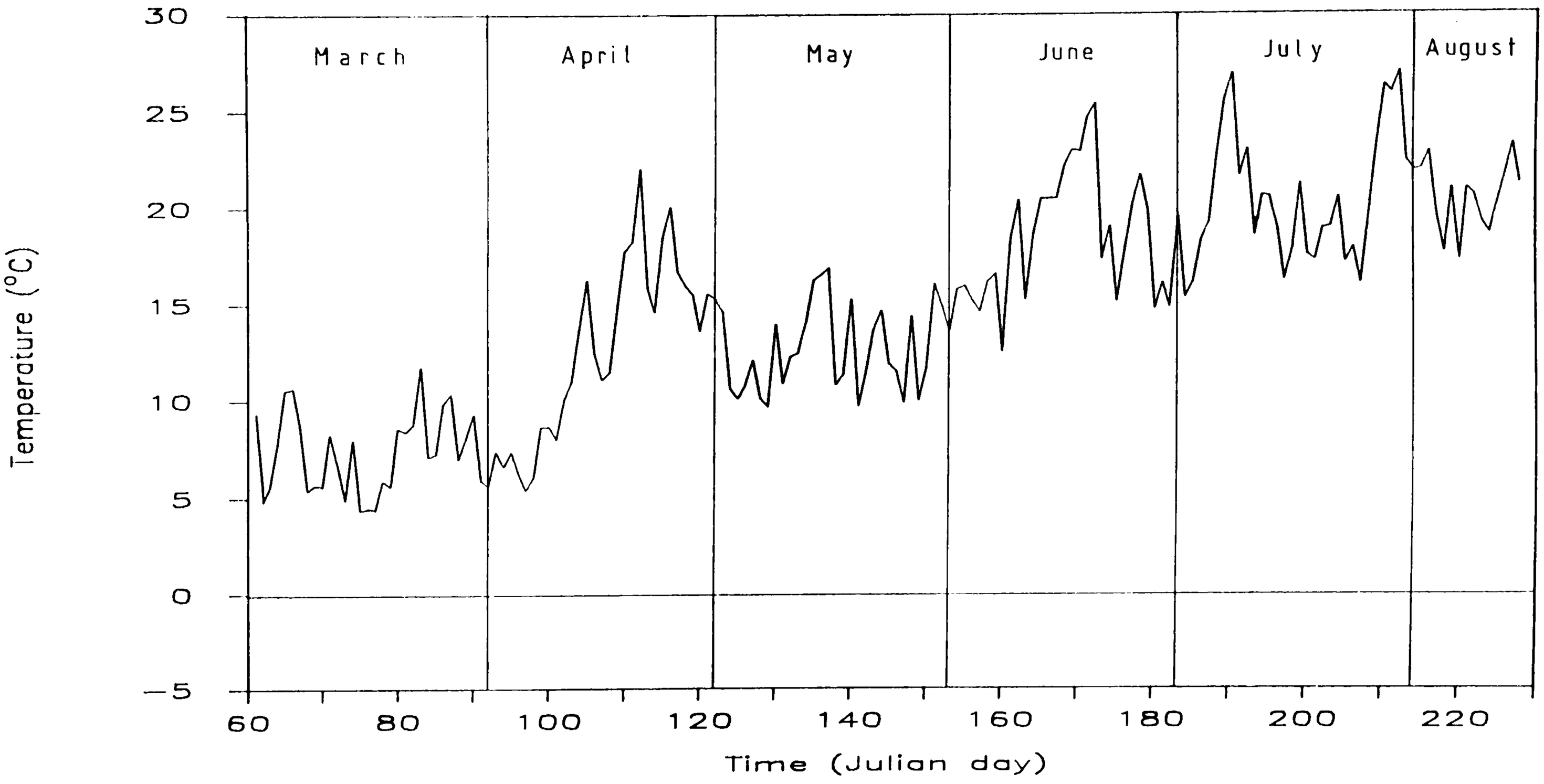

Figure A.2 Daily maximum values for temperature at the Norfolk Agricultural Station, Morley St. Botolph for the 1984 field season.

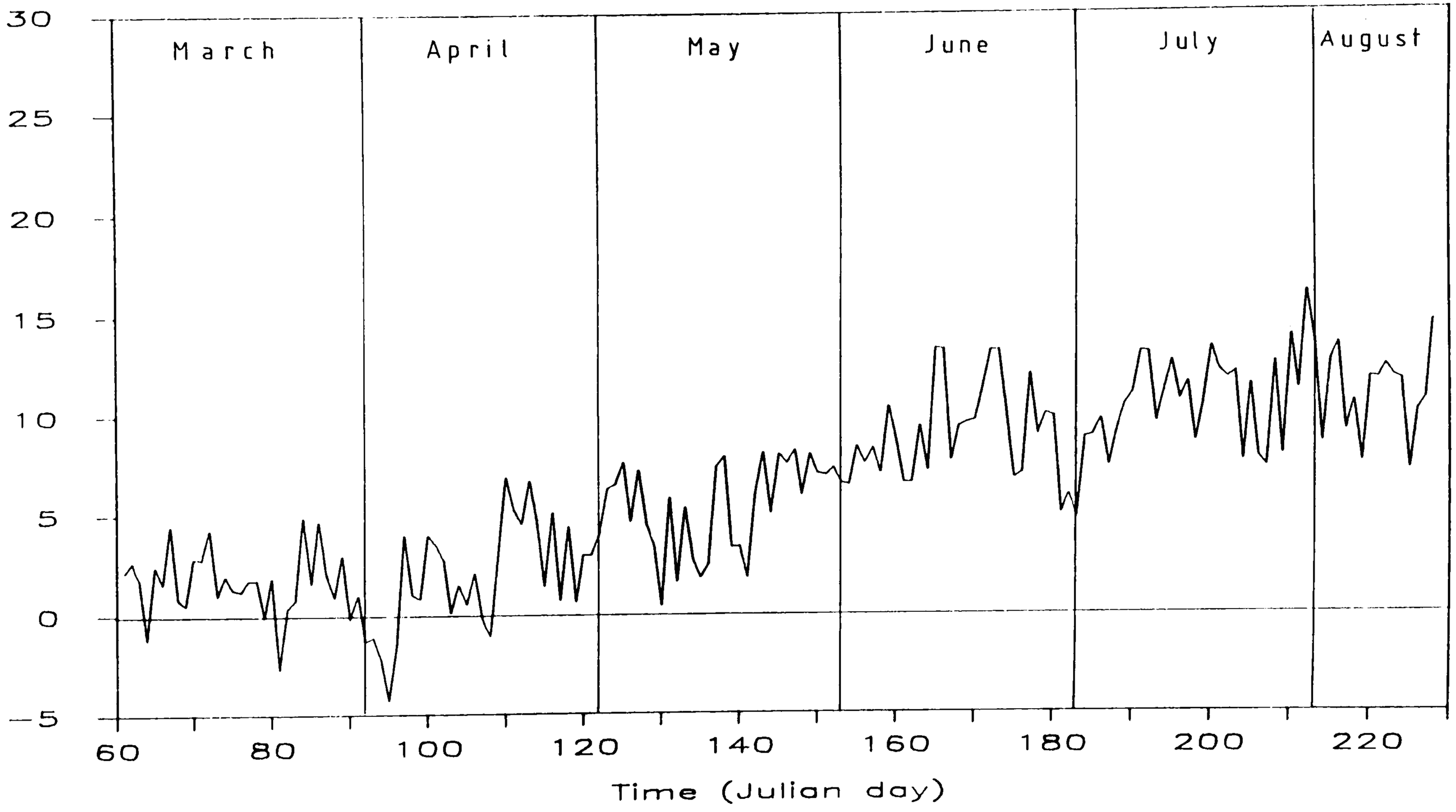

Figure A.3 Daily minimum values for temperature at the Norfolk Agricultural Station, Morley St. Botolph for the 1984 field season.

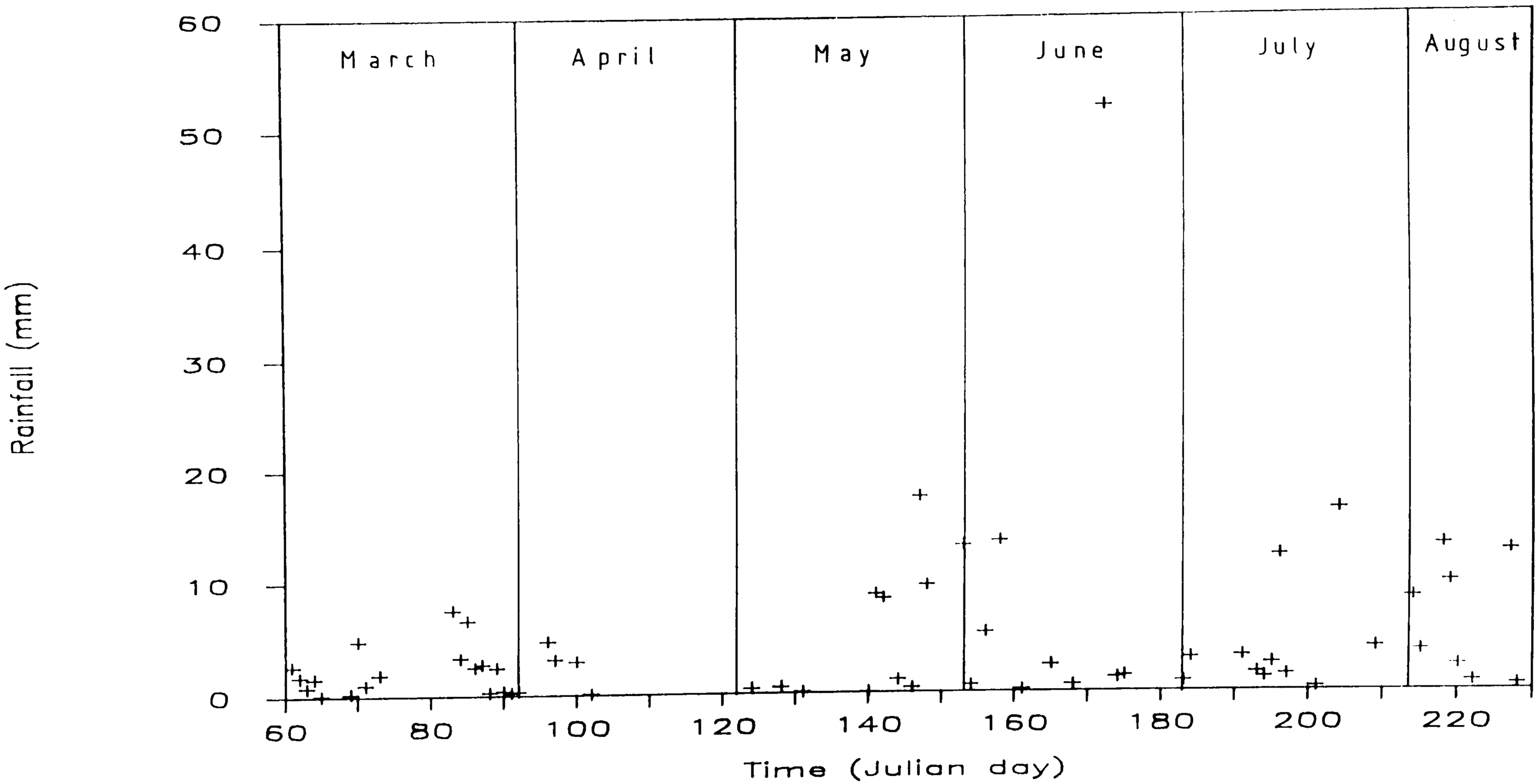

Figure A.4 Daily rainfall totals at the Norfolk Agricultural Station, Morley St. Botolph for the 1984 field season. Note especially the drought from April 10th to May 20th, and the exceptionally heavy rainfall on June 20th.

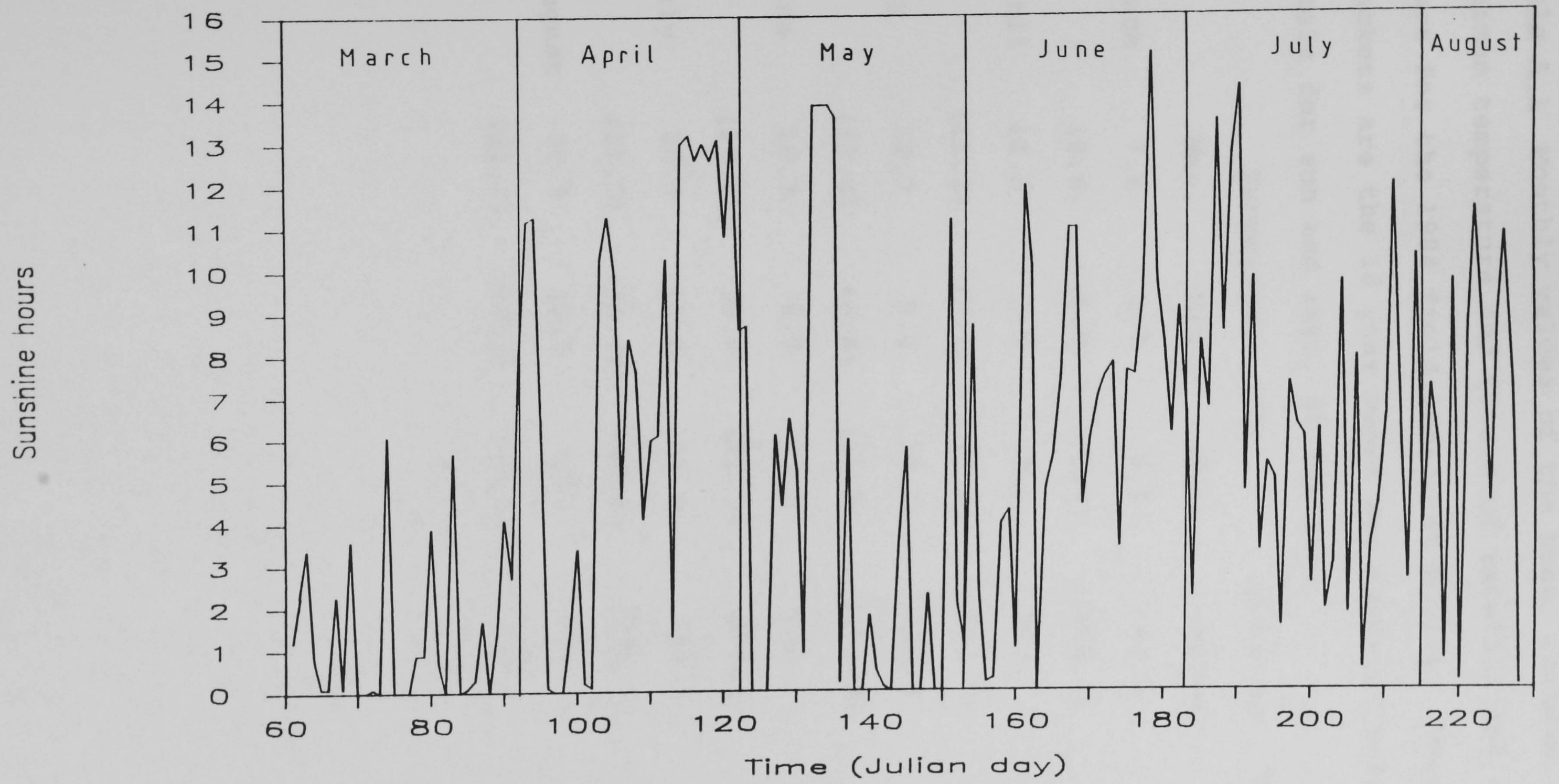

Figure A.5 Daily totals of sunshine hours for the Norfolk Agricultural Station, Morley St. Botolph for the 1984 field season.

Table A.1 Monthly values of the mean, maximum, and minimum temperature and totals of rainfall and sunshine hours for the 1984 field season at Morley. Values in brackets are the 18 year means for temperatures, and totals for sun and rain, at the site.

	Temperature (°C)			Sunshine	Rainfall
	Max.	Min.	Mean	(hours)	(mm)
March	7.4	1.7	4.6	42.5	41.4
	(8.6)	(1.9)	(5.2)	(102.5)	(46.6)
April	12.5	1.9	9.1	223.7	11.4
	(11.2)	(3.4)	(7.3)	(152.5)	(43.3)
May	12.7	5.4	10.1	129.3	47.0
	(15.4)	(6.4)	(10.9)	(191.3)	(49.2)
June	18.3	8.9	15.2	192.7	90.3
	(18.8)	(9.0)	(13.9)	(202.8)	(53.2)
July	20.3	10.6	16.6	190.5	46.1
	(21.0)	(11.0)	(16.0)	(195.3)	(47.7)
August	20.5	10.8	17.8	194.6	50.3
	(21.2)	(10.9)	(16.1)	(184.7)	(47.9)

APPENDIX II

Circuit diagrams

The following circuits were designed for this project and are described below:

i) Power and signal conditioning for the LEDA 1000 vane anemometers (designed with help from Dr Andrew Sandford of the Department of Forestry and Natural Resources in Edinburgh).

ii) Thermocouple amplifiers.

iii) Thermistors for use with the CR21 data logger.

iv) Voltage regulation to produce a ±5V supply for (i) and (ii) from a 12V battery.

All circuits were mounted on printed circuit boards.

The circuit for amplification of the signal from the drag sensor is described in Data sheet no. 6604, available from RS Components Ltd, Corby.

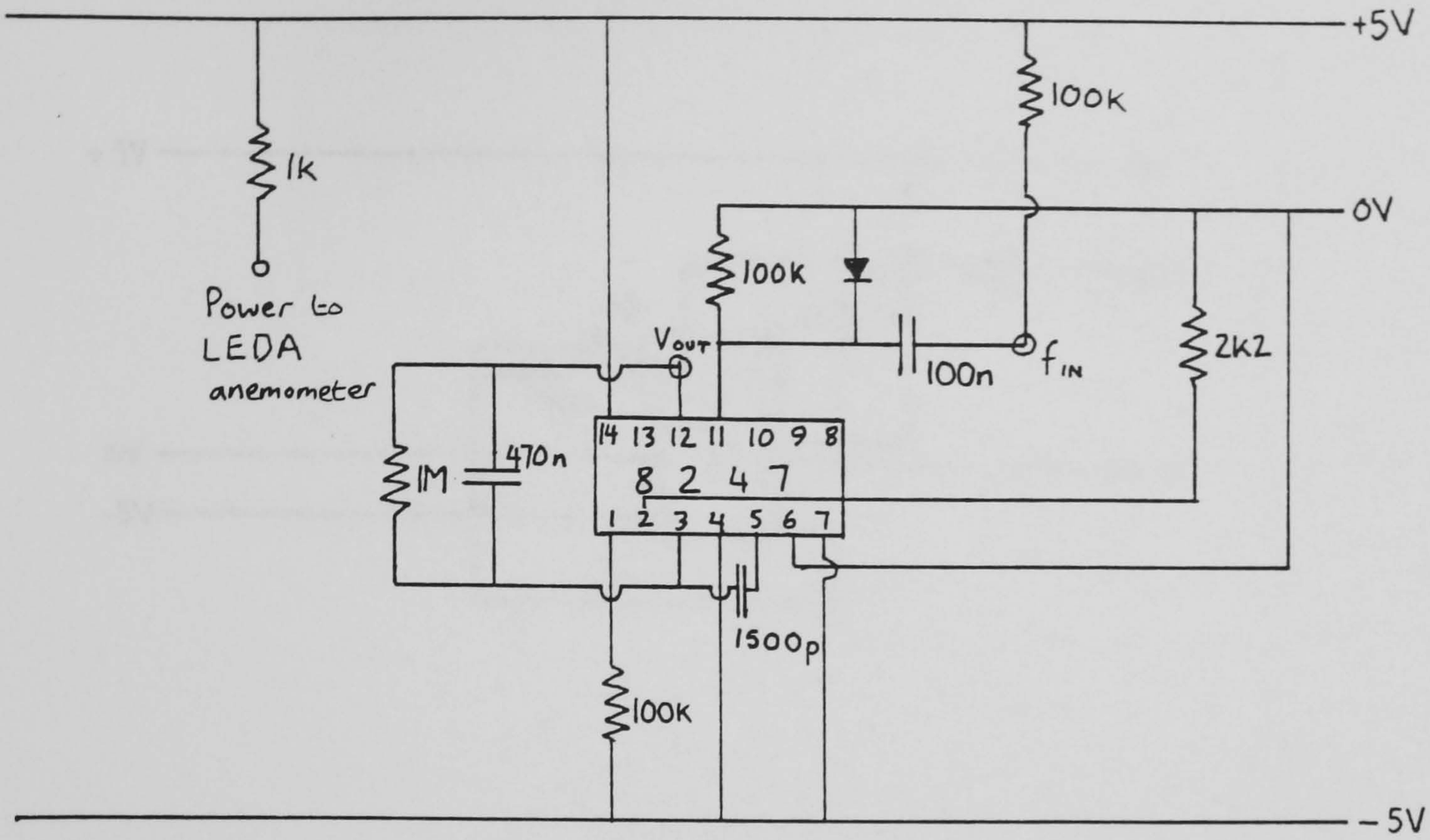

Figure A.6 Power and signal conditioning for LEDA 1000 vane anemometers.

Components list

For each anemometer:-

f/v converter

1 x type 8247

resistors

1 x 1k, 1 x 2k2, 3 x 100k, 1 x 1M

capacitors

1 x 100n, 1 x 470n, 1 x 1n5

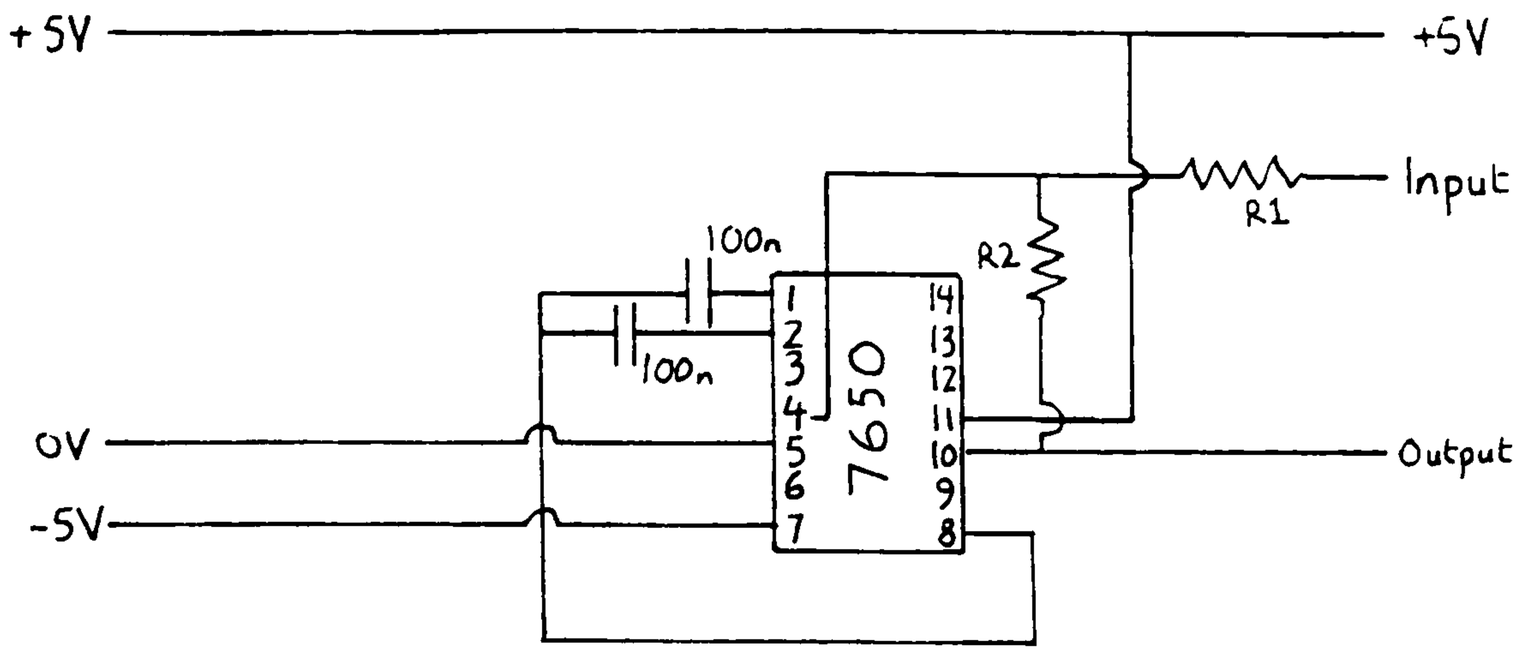

Figure A.7 Thermocouple amplifiers.

Components list

amplifier

1 x type 7650

capacitors

2 x 100n

resistors for reference thermocouple

R1 1 x 1k, R2 1 x 56k

resistors for gradient measurement thermocouples

R1 1 x 1k, R2 1 x 270k

Amplification in this circuit is calculated from

$$\text{Gain} = \frac{R1 + R2}{R1}$$

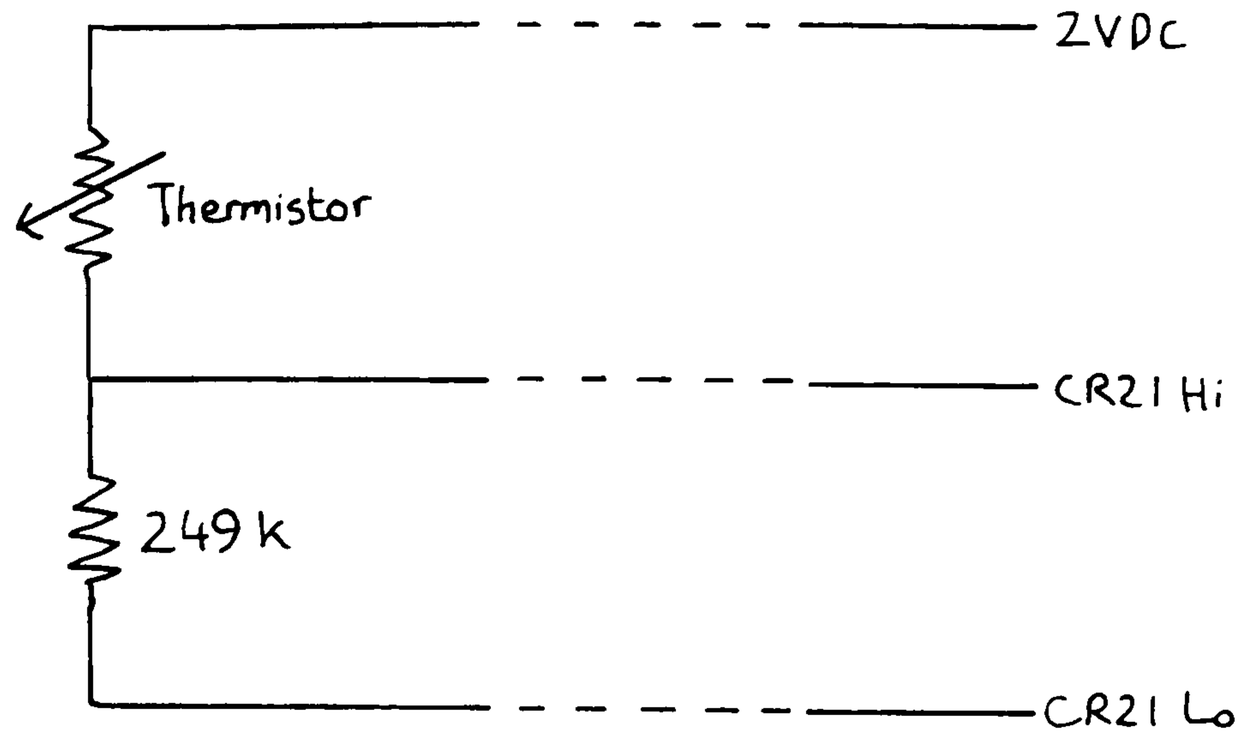

Figure A.8 Thermistor circuitry for use with the Campbell Scientific CR21 data logger.

Components list

thermistor

100k Fenwal model UUT51J1 or similar, eg. RS Components Ltd, Corby, stock number 151-243.

resistor

1 x 249k

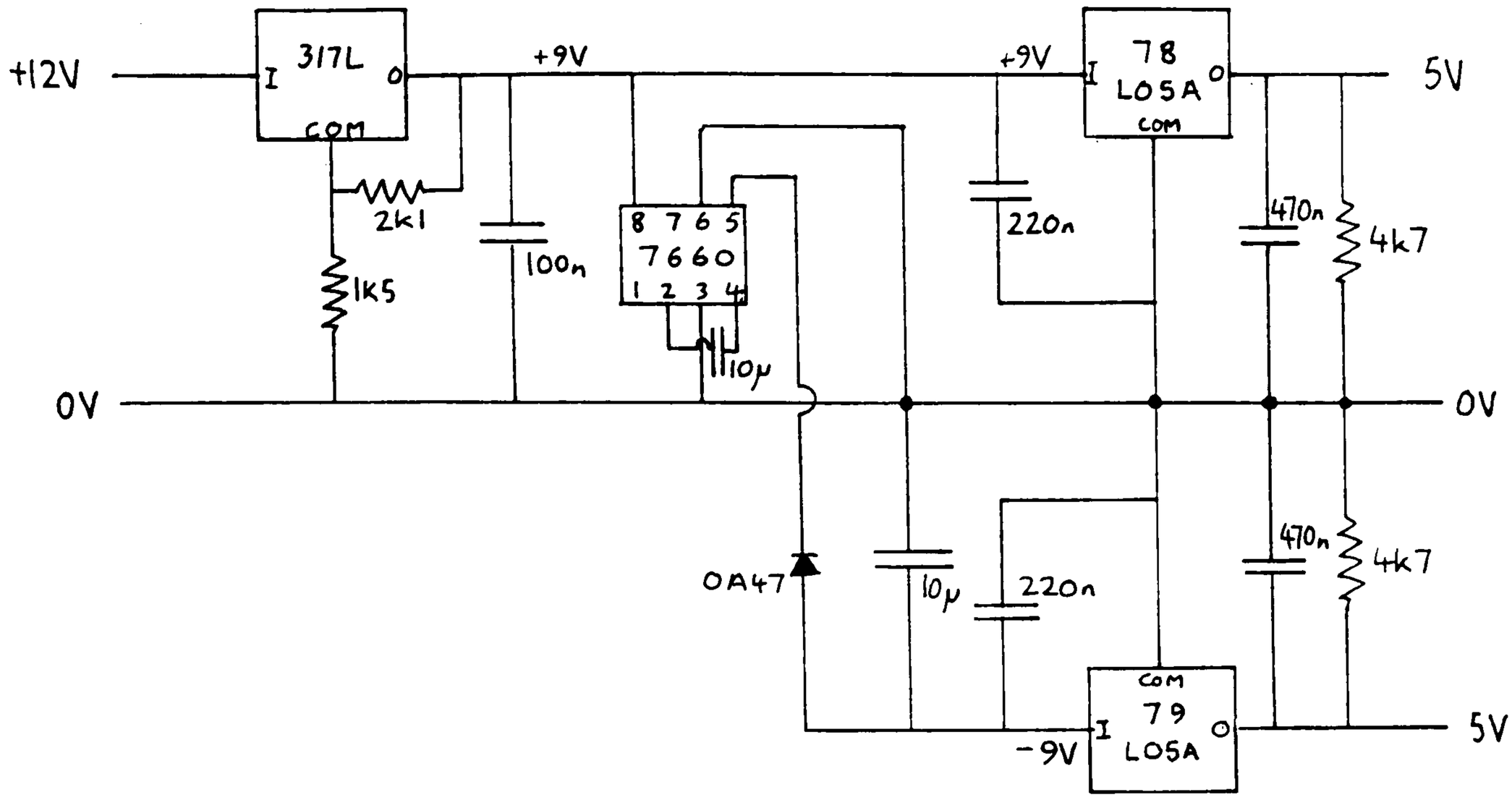

Figure A.9 Supply voltage regulation circuitry.

Components list

voltage inverter

1 x type 7660

regulators

1 x type 317L, 1 x type 78L05A,

1 x type 79L05A

diodes

1 x OA47

resistors

1 x 1k5, 1 x 2k1, 2 x 4k7

capacitors

2 x 220n, 2 x 470n, 1 x 100n,

2 x 10µ (electrolytic)

APPENDIX III

Methods for calculation of (d)

The usual methods for calculation of the zero plane displacement are the least squares method (Robinson, 1962, Stearns, 1970, Miranda, 1982) and algebraic methods such as that used by Landsberg and Jarvis (1973).

In both methods a series of test values of (d) are tried over the range of, say, 0.5(h) and 0.9(h). For the least squares method the correct value of (d) is that which gives the lowest sum of squares between measured and predicted $(u' - \bar{u})$ (from all data), where (u') = wind-speed at height (z) and $(\bar{u})$ = mean wind-speed. In algebraic methods the value of (d) used in equation 3.12 is altered systematically until equality is reached in the expression (or as close as the data permit).

A programme was written in Fortran77 to test both methods against idealised data and data containing errors. The subroutines for each method are shown overleaf. The idealised data set of 38 profiles was calculated for wind-speeds at heights of 1.5, 2.0 and 2.5 m above an imaginary crop with values of (d) ranging from 0.5 to 0.85 m, (z_0) from 0.1(d) to 0.2(d) for each value of (d), and (u_*) fixed at 0.35 m s^{-1}. Initial testing showed both subroutines were correct and predicted correct values for

all three parameters. Errors were then systematically introduced into the data in steps of 0.25% for the range 0 to 1%, and 0.5% for the range 1 to 3%. No consistent differences were found between methods with respect to error sensitivity. Of the three parameters (d) was most sensitive with a possible error of 38% resulting from a 1% error at one height. The corresponding worst case for (z_0) and (u_*) was 14.5% and 12.5% respectively. However, for an identical error at all three heights the error in (d) and (z_0) was minimal, with error in (u_*) only exceeding 1% for errors in wind-speed of 3%.

Whilst no real preference was found between the methods these results emphasize the need for care in profile measurement, and indicate the importance of proper alignment of sensors that show a directional response (like the vane anemometers used in this study).

Subroutine for least squares method

```
      SUBROUTINE PARAMS1 (Z1,Z2,Z3,U1,U2,U3,D,Z0,USTAR)
      REAL Z1,Z2,Z3,U1,U2,U3,D,Z0,USTAR,DTEST,Y1,Y2,Y3,
     *YMEAN,XMEAN,SSXY1,SSXY2,SSXY3,SSXY,SSYY,SLOPE,EEI1,
     *EEI2,EEI3,EEI,LSQ
C     Z1, Z2, Z3 = heights above canopy
C     U1, U2, U3 = wind-speeds at each height
C     D, Z0, USTAR = zero plane displacement, roughness
C                    length and friction velocity
C
      LSQ = 1000
      DO 20 DTEST = 0.4,0.9,0.01
         Y1 = ALOG(Z1-DTEST)
         Y2 = ALOG(Z2-DTEST)
         Y3 = ALOG(Z3-DTEST)
         YMEAN = (Y1+Y2+Y3)/3
         XMEAN = (U1+U2+U3)/3
         SSXY1 = ABS((U1-XMEAN)*(Y1-YMEAN))
         SSXY2 = ABS((U2-XMEAN)*(Y2-YMEAN))
         SSXY3 = ABS((U3-XMEAN)*(Y3-YMEAN))
         SSXY = SSXY1+SSXY2+SSXY3
         SSYY = (Y1-YMEAN)**2+(Y2-YMEAN)**2+(Y3-YMEAN)**2
         SLOPE = SSXY/SSYY
         EEI1 = ((U1-XMEAN)-(SLOPE*(Y1-YMEAN)))**2
         EEI2 = ((U2-XMEAN)-(SLOPE*(Y2-YMEAN)))**2
         EEI3 = ((U3-XMEAN)-(SLOPE*(Y3-YMEAN)))**2
         EEI = EEI1+EEI2+EEI3
C
C     Test value of EEI against current best LSQ
C
            IF (EEI.LT.LSQ) THEN
               D = DTEST
               LSQ = EEI
               USTAR = SLOPE * 0.41
               Z0 = EXP(YMEAN-((0.41*XMEAN)/USTAR))
            ENDIF
 20   CONTINUE
      RETURN
      END
```

Subroutine for algebraic method

```
      SUBROUTINE PARAMS2 (Z1,Z2,Z3,U1,U2,U3,D,Z0,USTAR)
C
C     Data were previously sorted such that Z1<Z2<Z3 and
C     hence U1<U2<U3.  See Subroutine PARAMS1 for
C     identification of variables.
C
      REAL Z1,Z2,Z3,U1,U2,U3,D,Z0,USTAR,X,Y,DTEST,
     *LSIDE,RSIDE
C
C     Calculate difference between the two sides of
C     equation 3.12 for values of DTEST.
C
      X = 1000
      DO 20 DTEST = 0.4,0.9,0.01
         LSIDE = (U3-U2)*ALOG((Z2-DTEST)/(Z1-DTEST))
         RSIDE = (U2-U1)*ALOG((Z3-DTEST)/(Z2-DTEST))
         Y = ABS(LSIDE-RSIDE)
C
C     Test current value of Y against that from previous
C     values for DTEST
C
      IF(Y.LT.X) THEN
         X = Y
         D = DTEST
      ENDIF
 20   CONTINUE
      RETURN
      END
```

APPENDIX IV

Worked examples

Calculation of wind profile stability correction parameters (chapter 3)

The first stage in the calculation of the stability correction parameter (ψ_1) given by Miranda (1982) is to calculate the dimensionless Richardson number (Ri).

Taking equation 3.2 to calculate (Ri), with the temperature gradient expressed as (dT/dz) in place of the gradient of potential temperature, ($d\theta/dz$), given that (Ri) is being calculated within a few metres of the earth's surface (see Rosenberg, 1974);

$$Ri = \frac{(g/T_a) . (dT/dz)}{(du/dz)^2}$$

In this example (ψ_1) is calculated for a height of 2 m where

$T_a = 293$ K

$dT/dz = -3$ K m^{-1} (the negative sign denoting that temperature decreases away from the surface)

$du/dz = 1$ m s^{-1} m^{-1}

Therefore, at this level,

$Ri = (9.81/293) \times (-3) / 1^2$

$= -0.1004$

Miranda (1982) gives the following expression for (ψ_1) equation 3.5;

$$\psi_1 = 2.\ln[(1+'x)/2]+\ln[(1+'x^2)/2]-2.\tan^{-1}('x)+\pi/2$$

Using the flux-profile relationships from Dyer and Hicks (1970) Miranda gives the following relationship (equation 3.5a) for ('x) under unstable conditions, as in this example;

$$'x = [1-16([z-d]/L)]^{1/4} = [1-16(Ri)]^{1/4}$$

Thus

$$'x = [1-16(-0.1004)]^{1/4} = 1.2707$$

Substituting this value into the equation for (ψ_1) above

$$\underline{\psi_1} = \underline{0.2846}$$

Values calculated in this way then allow the profile to be plotted as ($\ln[z-d]-\psi_1$) vs. wind-speed, as shown in figure A.10.

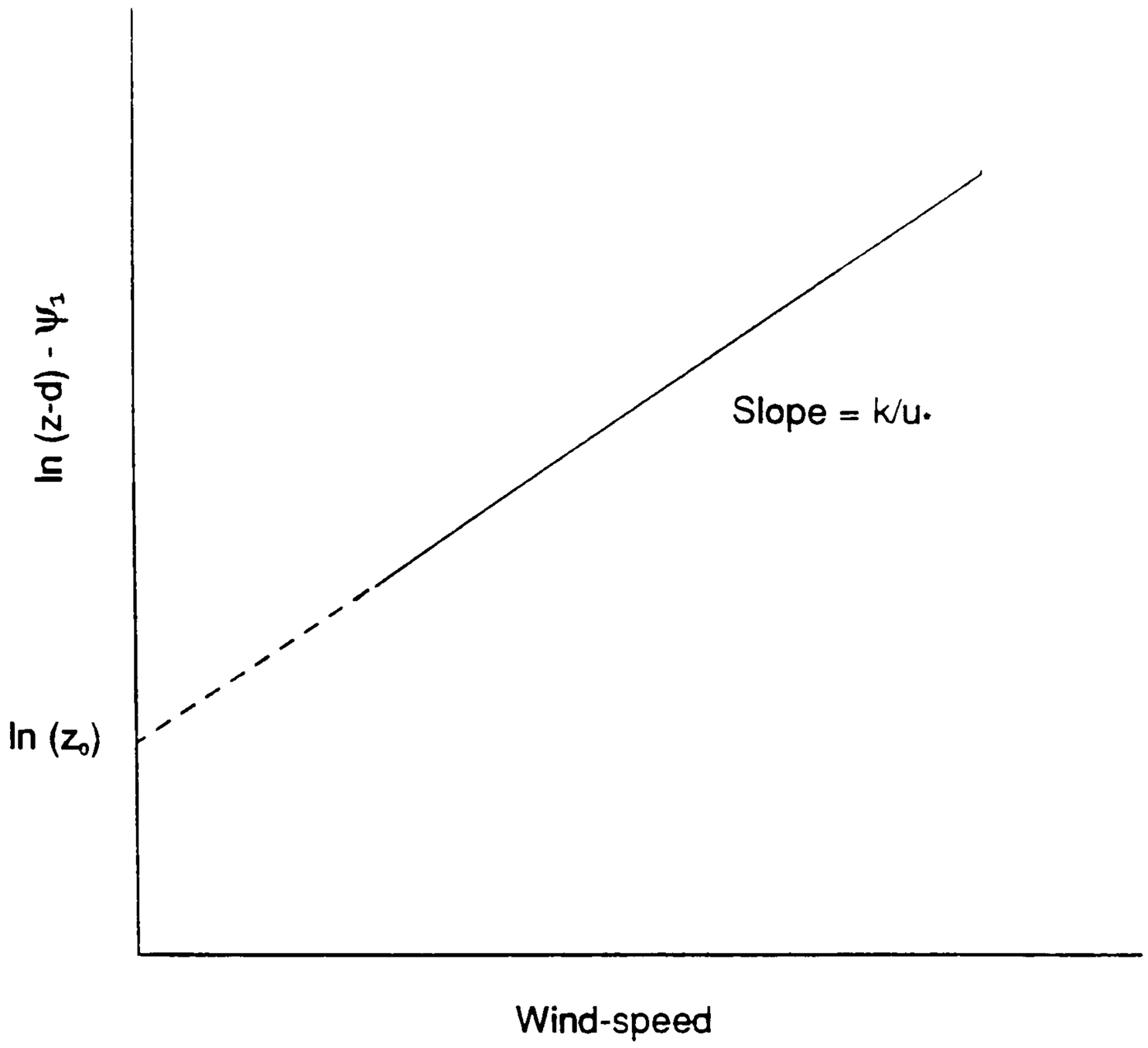

Figure A.10 Wind profile corrected for non-neutral stability conditions with $(\ln(z-d)-\psi_1)$ plotted against wind-speed.

Calculation of normalised shearing stresses (chapter 3)

Results from the conventional variety Maro at growth stage 4 are used in this example.

For the purposes of comparison between varieties, (τ) was given in figure 3.9 normalised for a wind-speed of 1 m s^{-1} at the height (h+1) m. For Maro at growth stage 4:

$h = 0.35$ m

$d = 0.25$ m

$z_o = 0.025$ m

Using the wind-profile equation 3.1 to calculate (u_*):

$$u_* = k.u(z)/\ln([z-d]/z_o)$$

$$u_* = (0.41 \times 1)/\ln([1.35-0.25]/0.025)$$

$$= 0.108 \text{ m s}^{-1}$$

Therefore, using equation 3.7a to calculate (τ) where

$$\tau = \rho.u_*^2$$

taking $\rho = 1.2$ kg m^{-3}

$$\tau = 1.2 \times 0.108^2$$

$$= \underline{0.014} \text{ N m}^{-2}$$

Calculation of bulk canopy drag coefficients (chapter 3)

Data for the semileafless variety Filigreen at growth stage 5 are used in this example:

Values of the bulk canopy drag coefficient (C_D) were calculated from equation 3.9, referenced to a level (d+1) metres above the crop:

$$C_D = k^2/(\ln[(z-d)/z_0])^2$$

$k = 0.41$

$z_0 = 0.038$ (see table 3.10)

hence referenced to the height (d+1) metres;

$C_D = 0.41^2/(\ln[1/0.038])^2$

$= \underline{0.0157}$

Calculation of shelter factors (chapter 4)

Results from the conventional variety Maro are used in this example.

The shelter factor, $(p_d) = f/\tau$

where f = the force acting on a crop calculated from measurements of drag coefficients of isolated canopy components in the wind tunnel, within-canopy wind profiles

and measurements of the distribution of crop area index within the canopy, and (τ) = shearing stress calculated from wind profiles measured above the canopy in the field.

Measurements of canopy structure for the variety Maro were taken when the crop was 0.75 m tall and in the stage where the canopy was drying out prior to collapse and harvest (corresponding to growth stage 6 for the wind profile measurements). Results from tables 3.10 and 3.12 show, for this stage, that

$$d/h = 0.600$$

$$z_o/h = 0.061$$

Therefore $d = 0.6 \times 0.75 = 0.45$ m

$$z_o = 0.061 \times 0.75 = 0.046 \text{ m}$$

Rewriting equation 3.1;

$$u_* = [k * u(z)] \Big/ \ln \frac{z - d}{z_o}$$

Therefore for a wind-speed of 5 m s^{-1} at the height (d+1) m,

$$u_* = (0.41 \times 5)/\ln(1/0.061) = 0.66 \text{ m s}^{-1}$$

(τ) was then calculated using equation 3.7 a;

$$\tau = \rho . u_*^2$$

Taking the value of (ρ) as 1.2 kg m^{-3},

$$\tau = 1.2 \times 0.66^2$$

$$\tau = \underline{0.53}\ \underline{\text{N}}\ \underline{\text{m}}^{-2}$$

The next stage was to calculate the predicted force acting on the canopy using equation 4.2;

$$f = \rho \int_0^h u(z)^2 . \sum [A_j . C_{dj}\{u(z)\}] \, dz$$

The method used in this study (like that used by Thom, 1971, was to calculate the force acting on leaves in each level of the canopy and the force acting on pods in each level, and then to add together all forces acting on the canopy to obtain a value for (f).

The following data were required; the measurements of leaf and pod area indices shown in chapter 2, the expressions for within-canopy wind profiles shown in chapter 3 and the drag coefficient measurements shown in chapter 4.

To calculate within-canopy wind-speeds using equation 3.11 from Thom (1971) (found in chapter 3 to give the best fit for the observed within-canopy profile of any published relationship), it is necessary to calculate the wind-speed at the top of the canopy (u[h]). Extrapolating the logarithmic wind profile (equation 3.1) to the height z = h = 0.75 m,

$$u(h) = (0.66/0.41) \times \ln([0.75-0.45]/0.046)$$

$$= 3.05 \text{ m s}^{-1}$$

Using equation 3.11:

$$u(z) = u(h).[1 + \alpha(1 - z/h)]^{-2},$$

where for Maro $\alpha = 1.77$,

the wind-speed at any height within the canopy may be calculated.

To calculate the force acting at each level leaf areas and pod areas (both per unit ground area) were taken from the results shown in figure 2.12. Drag coefficients for leaves and pods were taken from figures 4.10 and 4.12 respectively. These data and the calculated force acting at each level are shown in table A.2;

Table A.2

Height	Leaf Area	Pod Area	u(z)	Leaf C_d	Pod C_d	f(z)
0.075	0.550	0.000	0.453	0.50	0.63	0.068
0.225	0.619	0.007	0.608	0.47	0.63	0.131
0.375	1.101	0.063	0.858	0.41	0.63	0.433
0.525	1.327	0.116	1.301	0.37	0.63	1.145
0.675	1.075	0.171	2.200	0.30	0.63	2.500

Summing the force acting on each level for the total force,

$$f = 4.277 \text{ N m}^{-2}$$

$$p_d = f/\tau$$

$$= 4.277/0.53$$

$$= \underline{8.07}$$

The errors associated with (p_d) in table 4.1 were calculated from the 95% confidence limits for (z_o), as (z_o) has the greatest uncertainty attached to it of any of the variables used in the calculation of (p_d). For Maro at growth stage 6, (see figure 3.5) the 95% cofidence limits of (z_o) are ± 0.0062 m, (approximately 14%). Therefore,

z_o + 95% CL = 0.052 m

and z_o - 95% CL = 0.040 m

Repeating the above calculations using these values for (z_o) throughout (ie. for the calculation of both above and within canopy profiles) the following results are obtained:

p_d (for z_o + 95% CL) = 7.02

p_d (for z_o - 95% CL) = 9.36

These last two results (though more so the results for Filigreen and Filby shown in the main text above) illustrate the importance of accurate assessment of (z_o) if it is to be used in calculations such as that shown here.

Calculation of shearing stresses (chapter 5)

To produce an estimate of the maximum shearing stress likely to act on a crop it is necessary to have some idea of the maximum wind-speed likely in the pea growing areas of the U.K. during the growing season. From data presented in the Monthly Weather Report (HMSO, London) a maximum of about 40 m s^{-1} at a height of 10 m has been found (see table 5.1). It should be noted that wind-speeds are routinely measured for meteorological purposes at this height in order that local variations in the earth's surface will have little effect on the measurement. It therefore follows that it is unreasonable to expect (especially given the limited fetch available over most crops) it to be possible to predict very accurately the behaviour of the wind at heights where the flow is clearly affected by the surface, from measurements of wind-speed at 10 m. However, using profile results from chapter 3 it is possible to produce a rough estimate of the wind-speed just above a crop (at a height of 2 m, for example) due to (u[10m]) = 40 m s^{-1} from which maximum shearing stress can be calculated, in the following manner:

Using equation 3.1 (the log-linear wind profile equation) with a wind-speed at 10 m of 40 m s^{-1}, and values of (d)

and (z_o) for each variety just before lodging (growth stage 6) as given in tables 3.8 and 3.10 respectively, (u_*) was calculated for each variety.

$$u_* = k.u(z)/\ln([z-d]/z_o)$$

Taking the example of Filby (leafless), where

$d = 0.38$ m

$z_o = 0.036$ m

$u_* = (0.41 \times 40)/\ln([10-0.38]/0.036)$

$= 2.93$ m s^{-1}

Using these values we can estimate the wind-speed at 2 m from equation 3.1:

$$u(z) = \frac{u_*}{k} \ln \frac{(z-d)}{z_o}$$

Hence for Filby,

$u(2m) = (2.93/0.41) \times \ln([2-0.38]/0.036)$

$= 27.25$ m s^{-1}.

Doing the same calculations for the conventional and semileafless varieties, Maro and Filigreen, and pooling the results, a mean wind-speed at 2 m of about 26 m s^{-1} was obtained. For the sake of uniformity and comparability in results this figure was used as the estimate of the highest wind-speed likely at a height of 2 m over a mature

pea crop in the U.K.. Accepting the reasons given above, this value can only be regarded as approximate, though is adequate for the purposes of the present study at least.

(u_*) is now recalculated for this wind-speed, again taking Filby for the example:

$$u_* = (26 \times 0.41)/\ln([2-0.38]/0.036)$$

$$= 2.80 \text{ m s}^{-1}$$

Using equation 3.7a where

$$\tau = \rho . u_*^2$$

taking a value for (ρ) of 1.2 kg m^{-3};

$$\tau = 1.2 \times (2.80)^2$$

$$= \underline{9.41} \ \underline{N} \ \underline{m}_{-2}$$

Values calculated in this manner were then used in the estimation of forces acting on pea crops in the model described in chapter 5.

APPENDIX V

Stability conditions at Morley during wind profile measurement in the 1984 field season.

Variety	Growth stage	Dates	Mean (Ri)	Range
Filby	1	24, 25 April	-0.015	0.042 to -0.051
Maro	1	26, 27 April	-0.148	-0.105 to -0.216
Filby	2	3, 4 May	-0.087	-0.004 to -0.209
Filigreen	2	8, 9 May	-0.081	-0.051 to -0.100
Maro	2	9, 10 May	-0.178	-0.054 to -0.260
Filigreen	3	21, 22 May	-0.048	-0.016 to -0.124
Filby	3	24, 25 May	-0.005	-0.001 to -0.010
Maro	3	28, 29 May	-0.126	-0.058 to -0.179
Filigreen	4	1, 4 June	-0.028	0.012 to -0.122
Maro	4	5, 6 June	-0.011	0.052 to -0.122
Filby	4	7, 8 June	-0.034	-0.001 to -0.092
Filigreen	5	11, 12 June	-0.042	0.001 to -0.105
Maro	5	13, 14 June	-0.016	0.015 to -0.044
Filby	5	14, 15 June	-0.085	-0.037 to -0.159
Filby	6	25, 26 June	-0.067	-0.020 to -0.117
Maro	6	26, 27 June	-0.045	-0.027 to -0.072
Filigreen	6	27, 28 June	-0.231	-0.144 to -0.392
Filigreen	7	5, 6 July	-0.105	-0.060 to -0.156
Maro	7	9, 10 July	-0.064	-0.041 to -0.116
Filby	7	26, 27 July	-0.016	0.002 to -0.041

APPENDIX VI

Comparison of Vector cup anemometers with LEDA 1000 vane anemometers for profile mensuration

Whilst problems encountered with the LEDA anemometers prevented the collection of profile data above the crops with them for much of the season it is still of interest to compare their performance with the Vector anemometers both for future use and for evaluation of their suitability for the within-canopy measurements taken.

The values of (d) for which measurements with the LEDA anemometers were available are compared with the results from the cup anemometers in figure A.11. Differences between the two sets of data are seen to be small, especially for the data collected earlier in the season. An analysis of variance between the values calculated for each set of anemometers was carried out for each of the three points deviating most from the 1:1 line in figure A.11. This showed that for only one point was there a significant difference between estimates obtained with the vane anemometers and those obtained using the cup anemometers at the 5% significance level. It is concluded that this type of vane anemometer is suitable for measurement of profiles. It must, however be stressed

that as performance for this purpose is so heavily dependent on a similar cosine response between instruments, cosine response should be checked regularly.

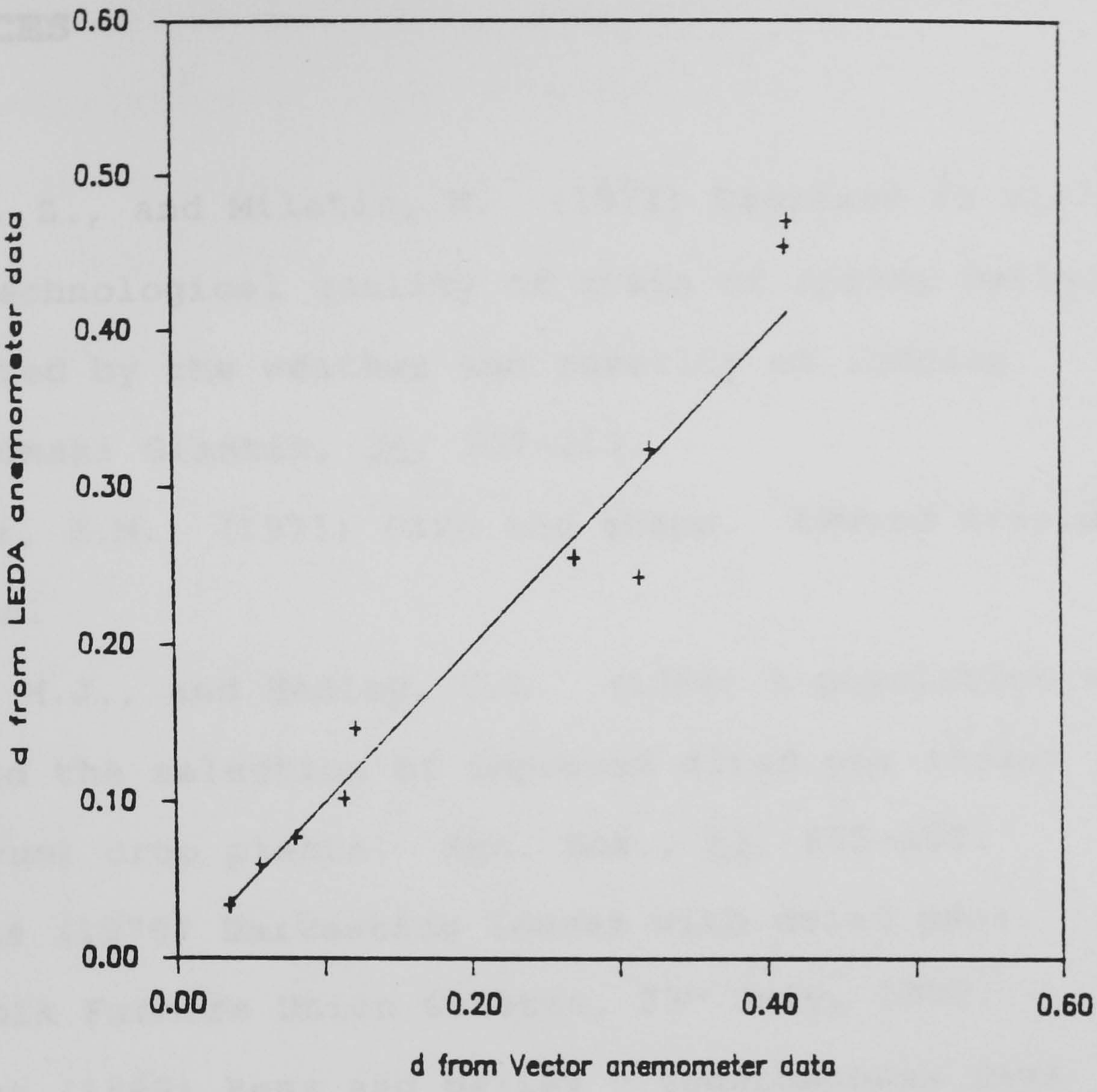

Figure A.11 Comparison of values of the zero plane displacement (d) calculated from profiles measured with Vector A100R cup anemometers and LEDA 1000 vane anemometers (with lightweight mica vane assembly). The 1:1 line is shown.

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